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Return Velocity and Drawdown
in Navigable Waterways

by Steve Maynord

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WES

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Return Velocity and Drawdown in Navigable Waterways

by Steve Maynord

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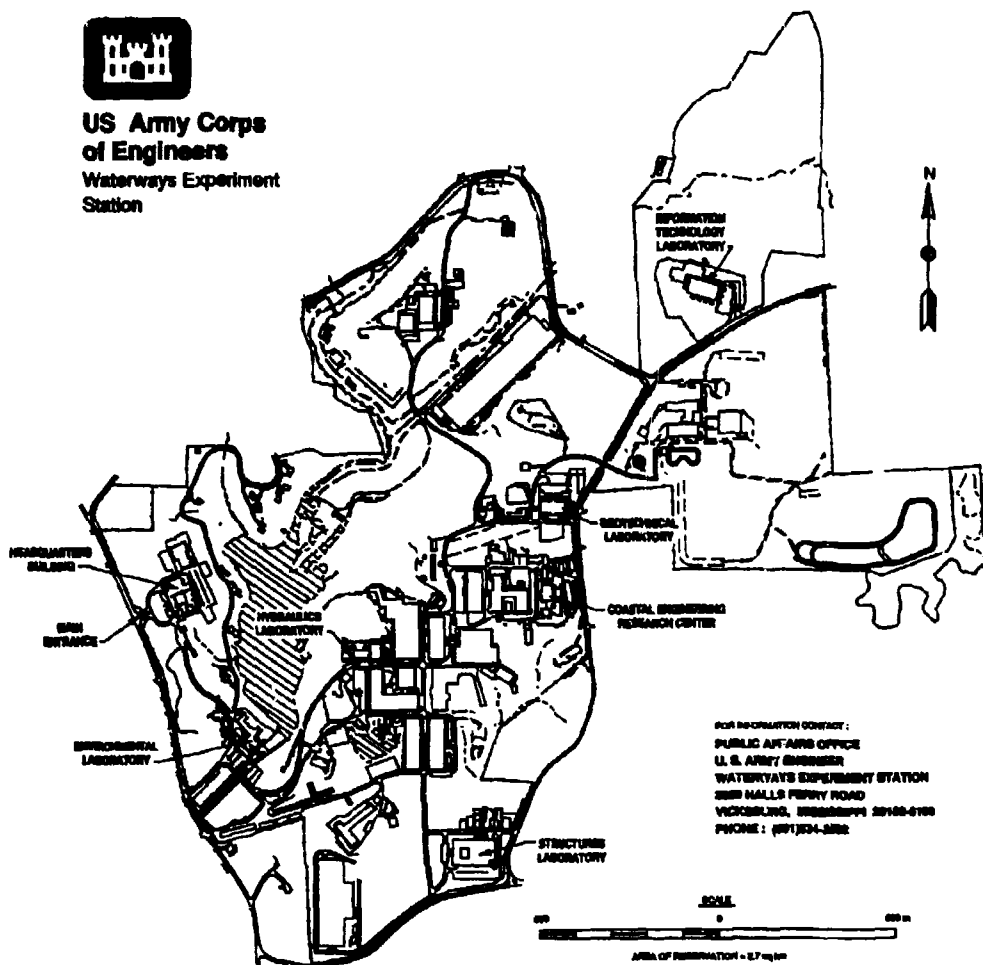Vicksburg, MS   39180-6199

Final report

US Army Corps
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Preface

The work described in this report was conducted at the U.S. Army
Engineer Waterways Experiment Station (WES) during the period June 1995
to September 1995. This investigation was sponsored by Headquarters, U.S.
Army Corps of Engineers (HQUSACE), under the Navigation Hydraulics
Research Program as part of the Civil Works Investigation Work Unit,
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Monitor Mr. Sam Powell.

The study was accomplished in the Hydraulics Laboratory (HL) under the
direction of Mr. Richard A. Sager, Acting Director; Mr. Robert Athow,
Acting Assistant Director; and Dr. Larry L. Daggett, Acting Chief, Naviga-
tion Division (HN). The study was conducted and the report was written by
Dr. S. T. Maynord, Navigation Effects Group, HN.

At the time of publication of this report, Director of WES was
Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

1 Introduction

Background

A vessel moving in a navigation channel displaces water and creates a flow of water (return velocity) alongside the vessel in a direction opposite that of the vessel. The magnitude of the return velocity is primarily dependent on vessel speed, channel cross section, and the submerged cross-sectional area of the vessel. The return velocity is also accompanied by a lowering of the water level alongside the vessel, drawdown, as well as other navigation effects shown in Figure 1. Return velocity and drawdown have been extensively studied in prismatic cross sections and confined or restricted channels, i.e., those having a low blockage ratio N, the ratio of channel cross-sectional area to vessel cross-sectional area. Previous studies (Permanent International Association of Navigation Congresses (PIANC) 1987, Schijf 1949) have addressed the channel stability aspects of return velocity and drawdown in
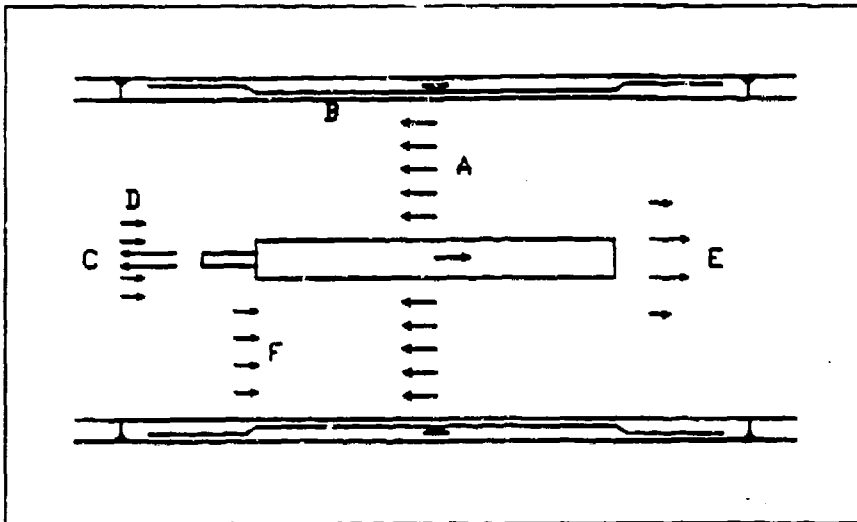
Figure 1. Navigation effects: A = return velocity; B = drawdown; C = propellor jet; D = wake flow; E = bow wave; and F = slope supply flow

confined channels. In other studies (Blaauw and van der Knaap 1983, Tothill 1966), a primary concern of drawdown has been the resulting lowering or squat that the vessel experiences when drawdown occurs. In confined channels, vessel speeds can be limited by vessel squat when depth/draft ratios are low.

In a general sense, return velocity and drawdown are analogous to pier or obstruction effects in a river. For piers that are small relative to the size of the river, large effects are found near the pier and negligible effects near the bank. If the pier took up a greater portion of the river, the effects would be large near the pier and significant near the bank. Finally, as the pier begins to dominate the cross section, the effects near the pier and near the bank are similar in magnitude. Because return velocity and drawdown follow these trends, mathematical decay functions whose shape varies with the vessel cross-sectional area relative to the cross-sectional area of the river are used to describe the distribution of return velocity and drawdown between the vessel and the bank line. For a large vessel size relative to the river, the decay functions should collapse to an almost uniform distribution from bank to vessel.

Return velocity and drawdown are of interest in assessing the effects of navigation on environmental concerns for large navigable waterways. Channel stability and vessel squat impacts due to return velocity and drawdown are often small in large waterways like the Ohio and Mississippi where blockage ratios become large. One exception is areas where vessels travel near bank lines such as in lock approaches. The analytical techniques for estimating return velocity and drawdown developed for confined channels are not directly applicable to large waterways because many basic assumptions used in their development are not met in large waterways.

Objective and Scope

This study develops techniques for estimating return velocity and drawdown from commercial vessels operating in navigable waterways and compares them to model and prototype data. Confined channel methods are modified to extend their application to large riverine navigation systems. The results are incorporated into the PC program NAVEFF with this report serving as the documentation. This study does not address other navigation effects such as waves or propeller flows shown in Figure 1. This report presents a modification and an expansion of the results presented in Maynord and Siemsen (1991) and uses data from shallow draft navigation on the Ohio, Illinois, and Upper Mississippi Rivers.

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2 Application of Confined Channel Methods to Large Waterways

Previous Confined Channel Studies

An excellent review of techniques to determine squat, drawdown, and return velocity in confined channels is presented by Blaauw and Van der Knaap (1983). Only the most pertinent studies are discussed in the following paragraphs.

Schijf's (1949) conservation of energy approach is frequently used in determining return velocity and drawdown in confined channels. The basic assumptions required in this approach are: uniform trapezoidal or rectangular cross section, uniform return current velocity from vessel to bank line, uniform drawdown from vessel to bank line, friction losses disregarded, uniform or negligible ambient velocity; and vessel on channel center line. Considering all motions relative to the vessel, continuity requires that

$$VA_c = A_w(V + V_r) \tag{1}$$

where

V = vessel speed

A_c = undisturbed channel area

A_w = disturbed channel area around midsection of vessel excluding A_m

V_r = average return velocity

---

[1] For convenience, symbols and abbreviations are listed in the notation (Appendix A).

$$A_m = \text{submerged cross-sectional area of the vessel at the midsection}$$

Conservation of energy requires that

$$\frac{V^2}{2g} + h = \frac{(V + V_r)^2}{2g} + (h - z) \tag{2}$$

where

g = gravitational acceleration

h = undisturbed average water depth

z = average water-level drawdown

The unknown quantities V_r and z can be determined from Equations 1 and 2. Differentiation of Equations 1 and 2 leads to a maximum speed (called the critical or limiting speed V_L) which can not be exceeded by a self-propelled vessel and has been verified in both model and prototype investigations. PIANC (1987) presents a coefficient β that varies with V/V_L in the Schijf equations to improve agreement between observed and computed return velocity and drawdown. The energy equation is rewritten as

$$\frac{V^2}{2g} + h = \frac{\beta(V + V_r)^2}{2g} + (h - z) \tag{3}$$

Gates and Herbich (1977) included the displacement thickness from boundary layer concepts to determine effective vessel draft and beam improving the agreement between Schijf equations and prototype measurements of vessel squat. Inclusion of boundary layer concepts partially addresses the assumption requiring that friction losses be disregarded.

Bouwmeester et al. (1977) reported that Schijf (1949) cannot be used even approximately for N greater than about 33 because water-level drawdown and return velocity are greatly nonuniform. Many tows in large waterways have a value of N greater than 33.

PIANC (1987) documented techniques for using the Schijf (1949) equations in channel stability investigations of prismatic channels. Schijf is recommended for B_o/B from 2 to 12, where B_o is the channel width and B is the beam of the vessel. Additionally, the ratio of channel width to vessel length L can be a significant factor in defining the ratio of maximum water-level drawdown to average water-level drawdown and maximum return velocity to average return velocity. Channels having a large ratio L/B_o will have a

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well-defined return velocity and drawdown time-history during the time the tow is adjacent to a given point on the bank.

Modification of Confined Channel Methods to Large Waterways

Some of the six basic assumptions for applying the Schijf equations are often not met in large waterways. The ambient and return velocities and the water-level drawdown are not uniform, the cross section is not prismatic, and the vessel is not on the channel center line. The equations determine average values of return velocity and drawdown. Maximum values near the shore are of the most interest for both channel bank stability and environmental concerns. Environmental interests often also require the variation in return velocity and drawdown between vessel and shoreline. The techniques presented here predict, at any given point between vessel and shoreline, the maximum deviation from ambient conditions due to return velocity and drawdown during the tow passage.

A major problem that must be overcome in evaluating asymmetric channels found in large waterways like the Ohio, Mississippi, or Illinois Rivers is how to handle tows off the channel center line. One technique assumes a mirror image on each side of the tow and computes average return velocity and drawdown. This is satisfactory until the tow gets near one bank line and far from the other resulting in a substantial amount of the return flow passing around the front of and beneath the tow. Then, the return current predicted on the side near the bank using the mirror image channel is much larger than actually occurs.

A second problem with the Schijf equation is in certain asymmetric channel shapes. Any channel with wide shallow areas on either or both channel sides is particularly subject to overestimating the return velocity at high vessel speeds. This problem becomes significant when tow speeds exceed about 90 percent of Schijf V_L for the total section and when the ratio of maximum depth to average depth exceeds about 1.3. Fortunately most tows are traveling at less than 0.9 V_L, normally from 50 to 75 percent of V_L.

Large Waterways Studies

Hochstein and Adams (1989) documented a technique for estimating return velocity on the upper Mississippi River that is used by Environmental Science and Engineering (ESE) (1981) and Simons et al (1988) and on the Ohio River by U.S. Army Engineer District, Huntington (1980). The average return velocity is defined as

$$V_r = V[(aB_T - B_T + 1)^{0.5} - 1] \tag{4}$$

where $a = (N/(N-1))^{2.5}$

For vessel speeds less than $0.65V_L$, where B_T is a coefficient defined as $B_T = 0.3 \exp(1.8V/V_L)$ and for vessel speeds equal to or greater than $0.65V_L$, $B_T = 1$. From Maynord and Siemsen (1991), the Schijf and Hochstein average return velocity equations give similar results for vessel speeds equal to 50 to 60 percent of Schijf V_L. In Equations 5 through 7, Hochstein presents a method for determining the return velocity distribution. A channel/tow width factor is defined as

$$\alpha = \max \left(1, 0.114 \, \frac{B_o}{B} + 0.715\right) \tag{5}$$

The maximum return velocity V_{rm} at the vessel is determined from

$$\tag{6}$$

$$V_{rm} = \alpha \, V_r$$

For $\alpha = 1$, the distribution of velocity is uniform from vessel to bank line. For $1 < \alpha < 1.5$, the distribution of return velocity is linear. For $\alpha \geq 1.5$, the distribution of return velocity is linear. For $\alpha \geq$, the distribution of return velocity from vessel to bank line is defined as

$$V_r(Y) = V_{rm} \exp(-Y/k) \tag{7}$$

where

$\quad V_r(Y) = $ maximum return velocity during tow event at distance Y from center line of vessel

$\quad k = B_{side}/(\alpha\{1 - \exp[-F(\alpha)\alpha]\})$

$\quad B_{side} = $ distance from vessel center line to shoreline

$\quad F(\alpha) = 0.42 + 0.52 \ln \alpha$

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ESE(1981), Simons et al. (1988), and USAED Huntington (1980) results showed that the Hochstein equations (Equations 4 through 7) underestimate measured return velocity.

Maynord and Siemsen (1991) presented a method for estimating return velocity in large waterways. Average return velocity is computed using Schijf (1949) without the correction factor. To handle tows navigating off the channel center line in asymmetric channels, the average return velocity is then proportioned on each side of the vessel using the following equation developed from physical model studies reported in Maynord (1990)

$$\frac{V_{rs}}{V_r} = C_1 \ SKEW + C_2 \tag{8}$$

where

$\qquad V_{rs}$ = average return velocity for each side of vessel

$\quad SKEW$ = $A_c/(2A_{side})$

$\qquad A_{side}$ = cross-sectional area from tow center line to bank line

Maynord and Siemsen (1991) used coefficients of $C_1 = 0.36$ and $C_2 = 0.64$ in Equation 8. The ratio α' of the maximum return velocity on each side of the tow V_{rsm} to V_{rs} is determined from

$$\frac{V_{rsm}}{V_{rs}} = \alpha' = \max \ [1,0.024N_{side} + 0.734] \tag{9}$$

where $N_{side} = 2A_{side}/A_m$.

Note the similarity between Hochstein's Equations 5 and 6 which use a width ratio and Equation 9 which uses an area ratio. As the area ratio (N_{side}) increases, the distribution of return velocity becomes nonuniform. From Equation 9, N_{side} less than 11 gives $\alpha' = 1$ and the distribution of return velocity between vessel and shoreline is uniform. The return velocity distribution from tow to bank line is determined from

$$\frac{V_r(Y)}{V_{rsm}} = \exp \ [-C(\frac{Y - B}{B_{side} - B})] \tag{10}$$

where

$$C = 1.2(\alpha' - 1) \tag{11}$$

$V_r(Y)$ is the maximum return velocity during the tow event for a given distance Y from the vessel center line. $V_r(Y)$ is linearly added to ambient currents for upbound tows and subtracted from ambient currents for downbound tows. Y must be greater than B, because from $Y = 0$ to $Y = B$ the velocity is also affected by flow under the barges which can be considerably larger than the return velocity. Based on a limited data set used in Maynord and Siemsen (1991), the Hochstein method underestimated the measured return velocities while the Maynord and Siemsen (1991) method overestimated the measured return velocities.

An obvious limitation of these distribution equations is that the distribution does not vary with the shape or local depth of an asymmetric cross section, although both methods do address a vessel off the channel center line. For the remainder of this report, Equations 1, 2, and 8 through 11 are referred to as the 1991 analytical method.

3 Return Velocity and Drawdown Data Sources, Errors, and Analysis

Prototype data on navigation effects have been collected on the Upper Mississippi, Illinois, and Ohio Rivers. One major limitation of these data is that only a few points were collected between the vessel and the bank line, primarily in the near-bank zone. Consequently, these data can not provide a verification of the velocity distribution shape and the return velocity magnitude outside the near bank zone. Physical model studies of reaches on the Upper Mississippi River were conducted where return velocity and drawdown were measured from shore to vessel to define the distribution of return velocity and drawdown. The physical model tests simulated a reach of the Illinois River near Kampsville and the Mississippi River near Clark's Ferry where the Illinois State Water Survey (ISWS) (Bhowmik, Soong, and Xia 1993a,b) conducted prototype measurements of tow-induced return velocity and drawdown. The physical model was verified by comparing model and prototype results for six tow events in each river reach. Agreement was reached between model and prototype return velocity and drawdown by reducing the physical model draft. Details of the Kampsville and Clark's Ferry physical model studies and the data used herein are provided in Maynord and Martin (1996a,b).

As with many data collection efforts, collection of return velocity and water level drawdown data is not an easy task in either the physical model or the prototype. Some error sources are specific to either model or prototype or applicable to both. Errors in instrumentation along with details of other potential error sources in the physical model testing are discussed in the physical model reports.

Instrument error in the ISWS prototype tests must be considered in using prototype data because of the environmental conditions found in the prototype. Electromagnetic velocity meters were used in the ISWS prototype studies and can be subject to a variety of problems. Radio interference can result in highly erratic readings. Drift can accumulate around the sensor head and modify readings in a manner that is not obvious to the person conducting the

tests. Nevertheless, the electromagnetic velocity meter is the best available prototype technique for this type of measurement. Wave data collected in the ISWS tests were frequently missing due to instrument malfunction.

Tow length and width are relatively easy to determine in the field as long as the tow is comprised of the standard 10.7 by 59.5 (35- by 195-ft) barges. When chemical barges are present, their nonuniformity of length and width can be a problem. Tow length is important because the length and time of passage past a given point are often used to determine the tow speed in proto- type tests. Tow draft may also contribute to the data scatter. Tows are assumed to draft 2.7 m (9 ft) if loaded and 0.6 m (2 ft) if unloaded unless contact with the towboat captain indicates otherwise. Mixed tows further complicate the issue.

Also the vertical location of velocity measurements is considered. Varia- tions caused by this effect are not as significant as it might first appear since tow-induced return velocity profiles are generally uniform. The boundary layer resulting from tow passage does not have sufficient time to completely develop into the typical velocity profile found in a fully developed open chan- nel flow. Therefore, velocity changes near the surface should be uniform down to the point where the boundary layer has developed. Results from the ISWS tests provided in Maynord and Martin (1996a) suggest that only meters 1001 and 998 (Figure 2) in the trip 1 data should not be used in the compari- son with the 1991 analytical method because of the boundary layer influence.

One of the greatest causes of data variability is determining the tow impact from the time-history of the parameter of interest. The difficulty of this task increases as the magnitude of the tow impact decreases, because it becomes more difficult to distinguish the tow impact from the natural variations present in the river. The first task in defining the tow impact is defining the ambient velocity prior to tow passage which can be a problem as there are some long period variations in the ambient velocity due to several factors such as changes in the regulating gates at the locks and dams. The next task is defin- ing the maximum deviation from ambient conditions. In the ISWS tests, the maximum (or minimum) value from an 11-sec moving average was selected during the time the tow was adjacent to the meter. This smoothing technique eliminated the normal variations present in turbulent flow while also defining the maximum value. The difference between the maximum value and the ambient was the tow impact.

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Note: Meters 998, 999, and 1000 are mounted on a platform at 0.31, 1.22, and 2.44 m above the bottom, respectively. The velocity meters are two dimensional electromagnetic meters. Details of the meter descriptions can be found in Bhowmik, Soong, and Xia (1993a).
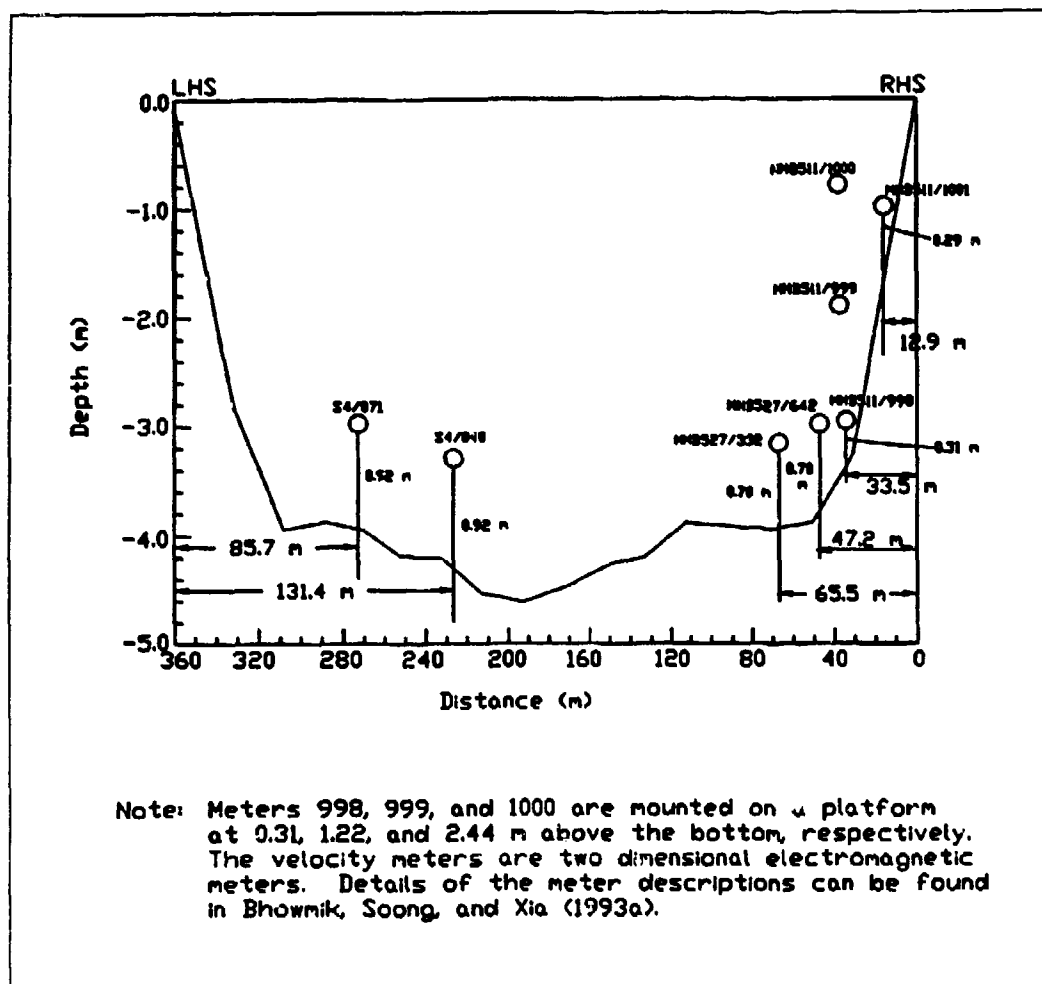
Figure 2. Cross section of the Illinois River at the Kampsville site for trip 1

4 1991 and 1995 Analytical Methods

Return Current Comparisons with 1991 Analytical Method

Tow speed used in application of the analytical methods was equal to the sum of vessel speed relative to the ground and the ambient velocity. Ambient velocity was positive for unbound tows and negative for downbound tows. Data were limited to tows with a length at least 40 percent of the channel width to eliminate the tow length effects measured in physical model tests of the Clark's Ferry reach being studied on the Mississippi River (Maynord and Martin 1996b).

A scatterplot of observed return velocity versus the predicted return velocity using the 1991 analytical method (Figure 3) was developed from the Kampsville physical model data. The 1991 analytical method under predicts return velocity observed in the physical model for most of the tests.

Comparison of the 1991 analytical method to the ISWS data required determining the draft, beam, and length to use for some unusual tow configurations having a mixture of loaded, unloaded, and partially loaded barges. The approach for this report selected the beam, draft, and length of the section having the maximum cross-sectional area.

A scatterplot (Figure 4) of observed prototype return velocity versus the predicted return velocity from the 1991 analytical method was developed from ISWS Kampsville prototype test data. As in the physical model, prototype data were limited to tows with a length greater than 40 percent of the channel width. N less than or equal to 51 was used to agree with the limits of the physical model data. Meters 998 and 1001 from trip 1 were excluded because their close proximity to the boundary (0.31 m) led to boundary layer effects. As in the physical model, the 1991 analytical method under predicts observed prototype return velocity for most tests.
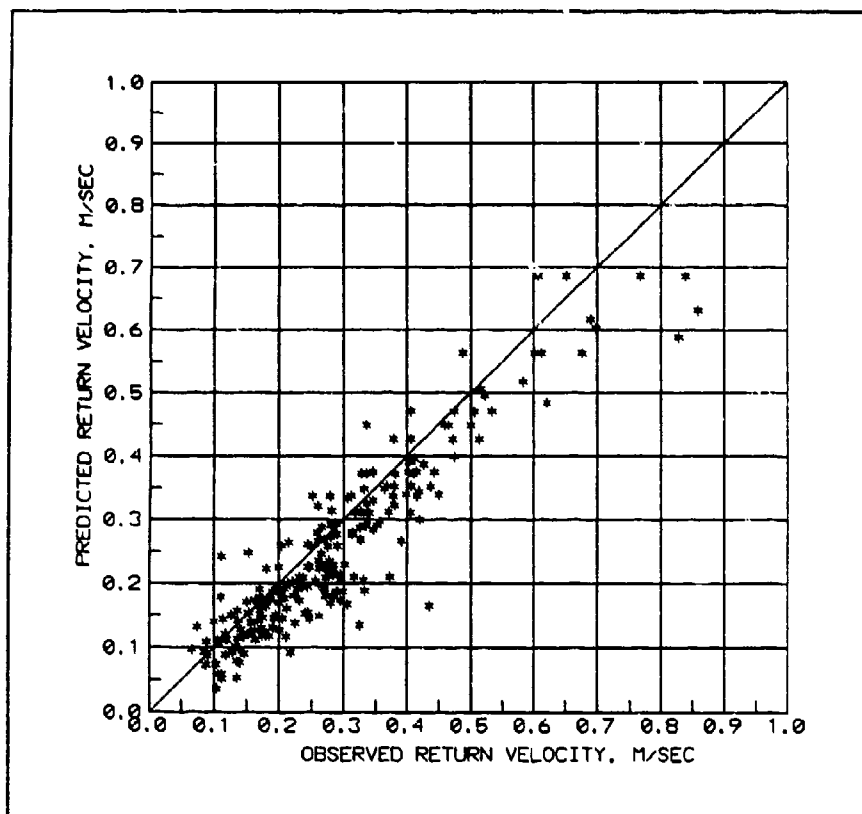
Figure 3. Observed physical model return velocity versus computed return
velocity using 1991 analytical method

1995 Analytical Method

Based on the underprediction of both physical model and prototype results,
the 1991 analytical method must be reexamined. The physical model data
from Kampsville and Clark's Ferry provided an opportunity to evaluate each
part of the 1991 method. The maximum return velocity $V_r(Y)$ during the tow
event for each meter is the value extracted from the model and prototype data.
The $V_r(Y)$ data from the eight physical model meters from the Kampsville
and Clark's Ferry physical model data were averaged to determine the return
velocity representative of the entire cross section V_r. Since $V_r(Y)$ is the
maximum return velocity during the tow event at Y, V_r is a cross-sectional
average of these maximums. The ratio Vr/Schijf Vr (from Eq's 1 and 2) was
compared for upbound versus downbound vessels to determine if the average
channel velocity is the correct velocity to use in determining the velocity of
the tow relative to the water. A likely alternative is the velocity where the
tow is operating which is generally greater than the average channel velocity.
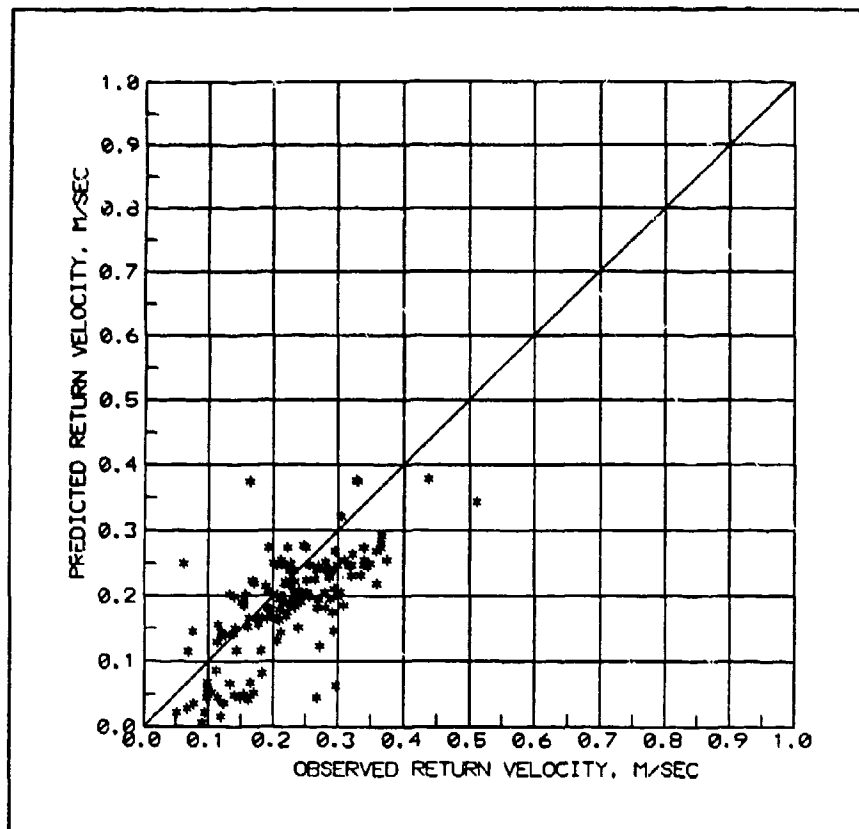
Figure 4. Observed prototype return velocity versus computed return
velocity using 1991 analytical method

The average Vr/Schijf Vr for upbound tows was higher than the average
ratio for downbound tows when using the average channel velocity to deter-
mine the vessel speed through the water. When the average channel velocity
was increased by 20 percent and then used to determine the speed through
the water, upbound and downbound tows gave the same average ratio. This
finding tends to confirm the use of the velocity where the tow operates when
determining the tow speed through the water. The 20-percent increase is
consistent with the actual velocity that occurs in the deeper areas where the
tow is operating

The Schijf return velocity, calculated using Equations 1 and 2 with the
20-percent increase in $Vavg$, under predicted the observed cross-sectional
average of the maximum Vr from the physical model. To correct this under-
prediction, an effective draft and beam were determined by adding the dis-
placement thickness to the draft and twice the displacement thickness to the
beam of the vessel as recommended by Gates and Herbich (1977). Displace-
ment thickness is determined from the Prandtl-Schlicting skin friction

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equation for a smooth flat plate at zero incidence (Schlicting 1968). Displacement thickness δ_1 is determined from the skin friction equation according to

$$\delta_1 = \frac{0.292\ L}{(Log(R_L))^{2.58}} \tag{12}$$

where

L = total barge length

$R_L = V_{disp}\ L/\nu$

$V_{disp} = V_s + V_{amb} + Schijf\ Vr$

V_g = vessel speed over the ground

V_{amb} = positive for upbound tows and negative for downbound tows

ν = kinematic viscosity of water

While this significantly improved the comparison between observed average V_r and V_r(Schijf), the error between the two was a function of the ratio of vessel speed to the critical or limiting speed (V_L) from Equations 1 and 2. Dependence with V/V_L is consistent with the findings of Schijf (1949). The observed physical model data were used to develop a correction factor based on V/V_L which provided good agreement between observed average V_r and Schijf V_r. Schijf V_r is calculated using the effective draft and beam in the Schijf equation. Average V_r is calculated from

$$V_r = V_r(Schijf)\ (1.9-1.29V/V_L) \tag{13}$$

The computed V_r from Equation 13 is not allowed to be less than the return velocity from the Schijf equation and V/VL should be from 0.35 to 0.9. The comparison between observed V_r from the Kampsville and Clark's Ferry physical models and computed V_r using Equation 13 is shown in Figure 5. Since δ_1 is computed using V_r from equations 1 and 2, the solution does not require iteration with Equation 13.

The next step is evaluating the relationship in Equation 8 that proportions the return velocity on each side of the vessel. The return velocity for each side of the vessel V_{rs} was determined for each test using the Kampsville and Clark's Ferry physical model data. V_{rs} was normalized by the observed
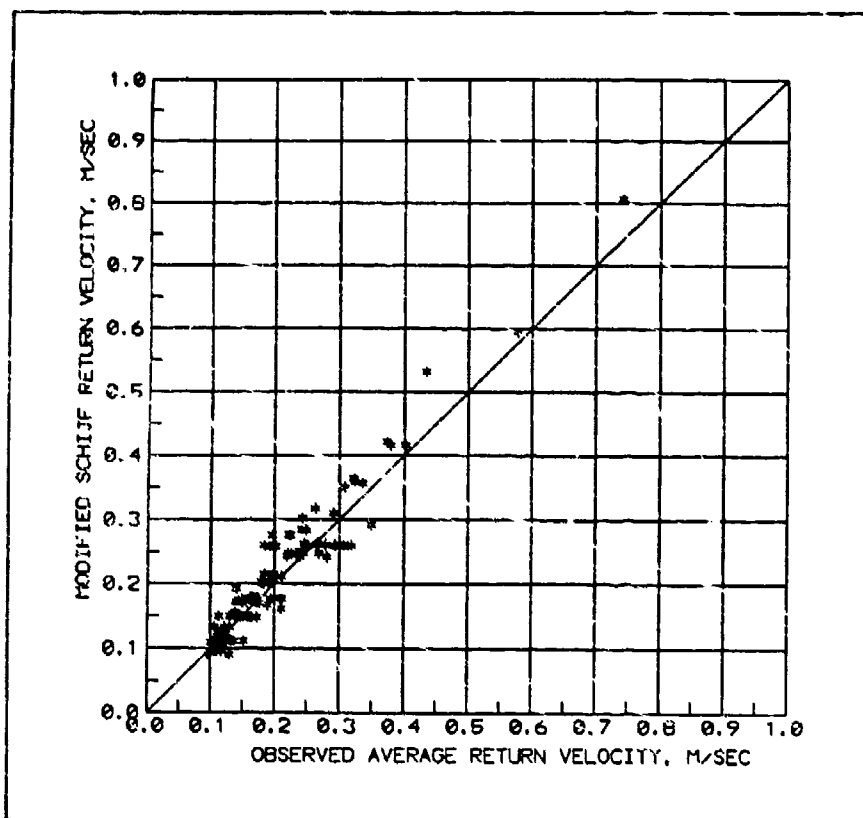
Figure 5. Observed physical model average return velocity versus computed
Schijf return velocity

average V_r (which represents the entire cross section) and tested against
various parameters such as SKEW used in Equation 8. The best fit was
found using the relation between distance from vessel to shoreline B_{side} and
total channel width B_{total}. For B_{side}/B_{total} from 0 to 0.5

$$\frac{V_{rs}}{V_r} = 1.65 - 1.3\frac{B_{side}}{B_{total}}$$

(14)

For B_{side}/B_{total} from 0.5 to 1.0

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$$\frac{V_{rs}}{V_r} = 1.35 - 0.7 \frac{B_{side}}{B_{total}}$$

(15)

Equations 14 and 15 are plotted against observed data from the Kampsville and Clark's Ferry physical models in Figure 6 along with rectangular flume data from a previously unpublished data set.
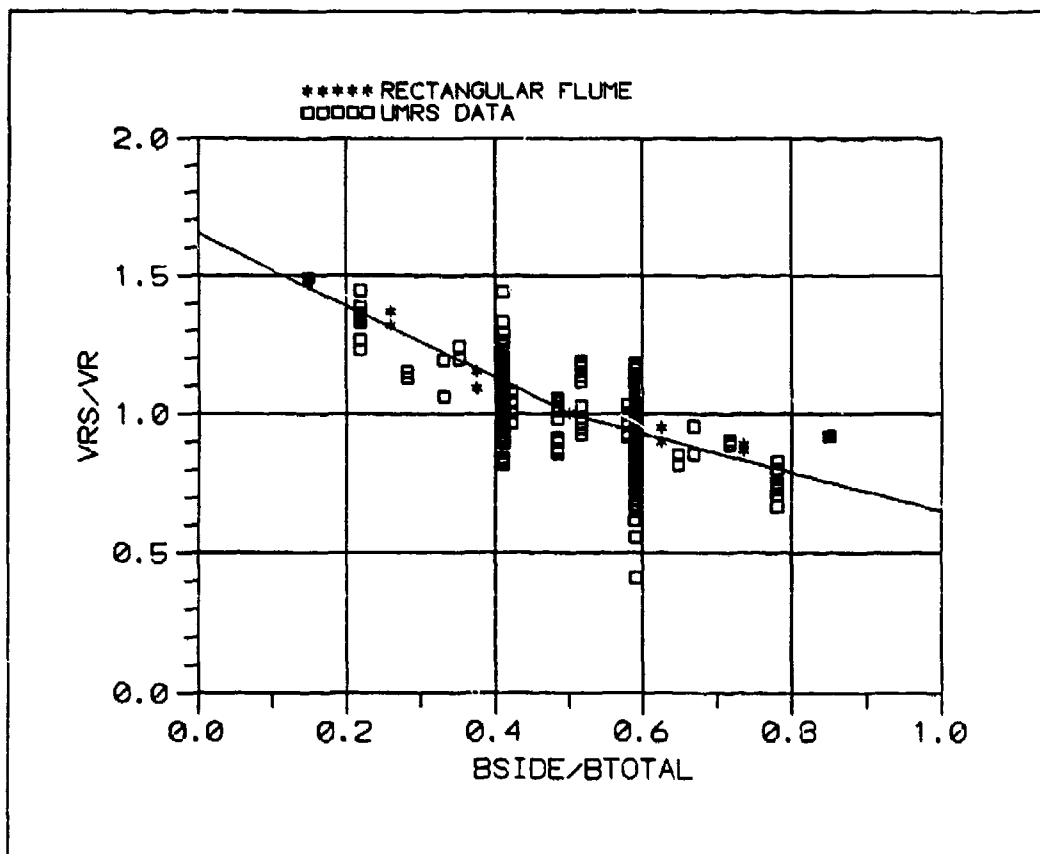
Figure 6. V_{rs}/V_r versus B_{side}/B_{total} using physical model data

The third step is defining $\alpha' = V_{rsm}/V_{rs}$ which defines the uniformity of the return velocity distribution between vessel and shoreline. Previous attempts at this relation using physical model data were only approximate because scale effects were not eliminated from the data as has been done in the Maynord and Martin (1996a,b) physical model data. Only the physical model data from the Kampsville model were used in the analysis of α' because of the likely influence of dikes from the Clark's Ferry model. The

physical model data were used to determine V_{rsm} at $(Y-B)/(B_{side}-B) = 0$. Various parameters were tested against α', and N_{side} provided the best agreement with observed data. V_{rsm}/V_{rs} is plotted against N_{side} in Figure 7 and is described by the equation

$$\frac{V_{rsm}}{V_{rs}} = \alpha' = 0.75 N_{side}^{0.18} \qquad (16)$$
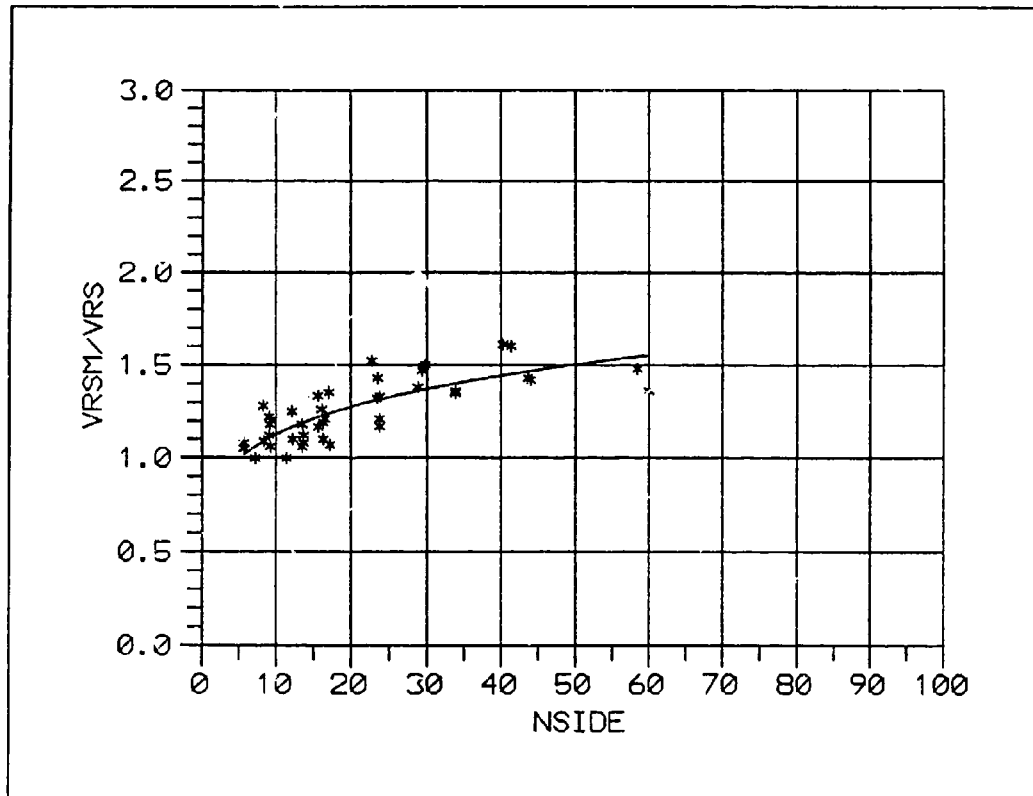
Figure 7. V_{rsm}/V_{rs} versus N_{side} using physical model data

The final step was determining C in Equation 10 which describes the shape of the return velocity distribution. One requirement of C is that it must equal zero for $\alpha' = 1$. The C that best defines the shape of the return velocity distribution in the physical model data from Kampsville and Clark's Ferry is defined by

$$C = 3.0 \ln (1/\alpha')$$

<div align="right">(17)</div>

The revised equations presented above will be referred to hereafter as the 1995 analytical method. A scatterplot of the Kampsville physical model data versus the 1995 analytical method (Figure 8) shows an improved comparison of observed versus predicted return velocity. Individual test plots for the Kampsville physical model are shown in Figures 9 to 13. The six plots on each figure for individual tests having varying speed, position, upbound versus downbound, etc. In the test number, the K stands for Kampsviile and L or H for low or high flow. R or L stand for right or left of the channel thalweg and U or D stand for upbound or downbound. If neither R or L appear before U or D, the tow is on the channel thalweg. The last three numbers give the vessel speed relative to the ground in model meters per second which can be converted to prototype values for the 1:25 Kampsville model by multiplying by $25^{1/2} = 5$. Details of each test are given in Table 1. On some of the physical model tests, the exponential type equation given by Equation 10 underpredicts the return velocity at the bank. Other data sets will be examined to see if this trend is repeated. A scatterplot of the Clark's Ferry physical model data versus the 1995 analytical model is shown in Figure 14 for N less than 52. Figure 15 provides a scatterplot of tests conducted with pool 572.7 in the Clark's Ferry section which resulted in N of about 85. The tests in Figure 15 addressed the open river portion of the Upper Mississippi River where large channel cross sections result in large blockage ratios. The 1995 analytical method, derived from physical model data, was then evaluated using the ISWS data. Scatterplots of prototype data from Kampsville and Clark's Ferry are shown in Figures 16 and 17, respectively. Individual plots for the ISWS prototype data at Kampsville are shown in Figures 18 to 21. Each of the 24 plots in Figures 18 to 21 represent an individual prototype tow with the towboat name given in the upper right-hand corner. Plots where there are two or more points at the same distance from the tow are locations where velocity meters were placed at different vertical positions. Details of the prototype tests are provided in the Table 2 report. Note that the Kampsville prototype data do not show evidence of an increase near the bank.
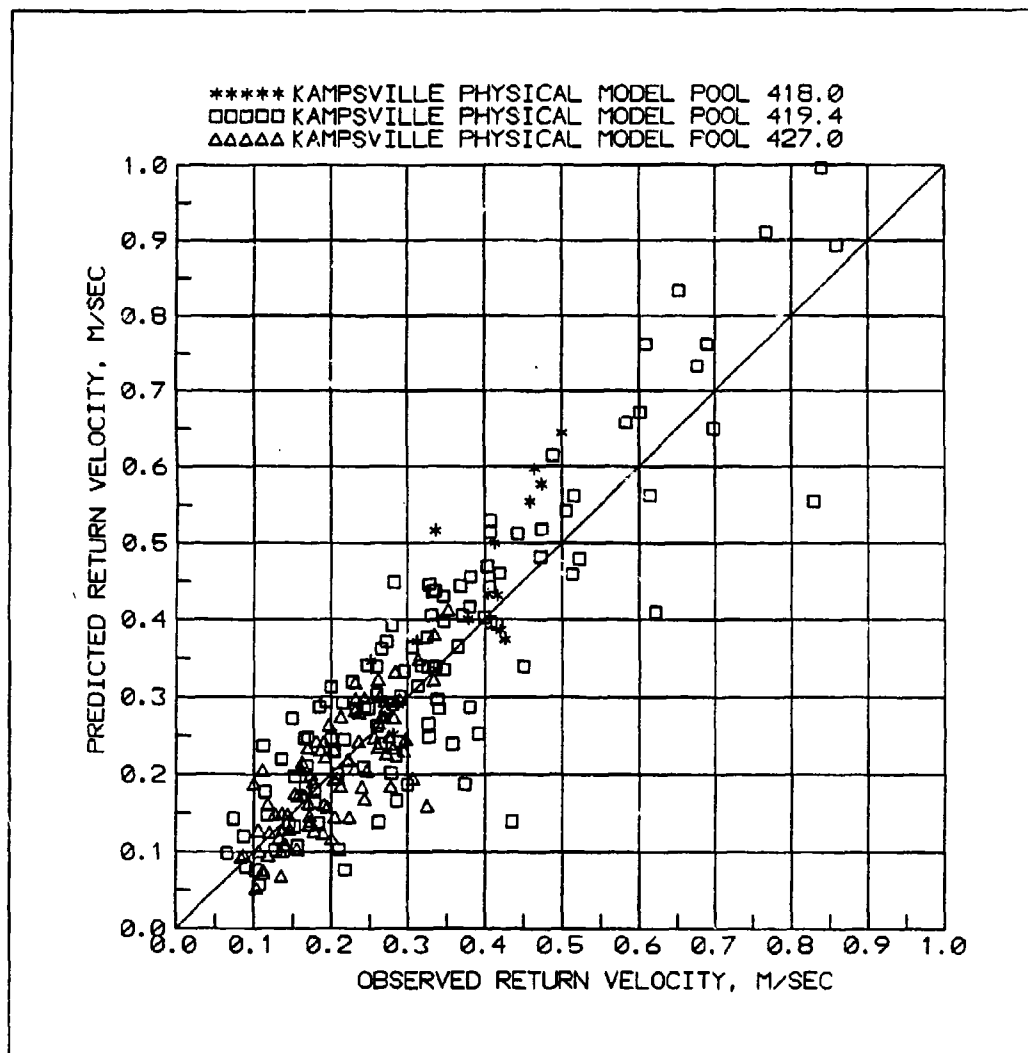
Figure 8. Observed Kampsville physical model return velocity versus computed return
velocity using 1995 analytical method

a. Test KLU335
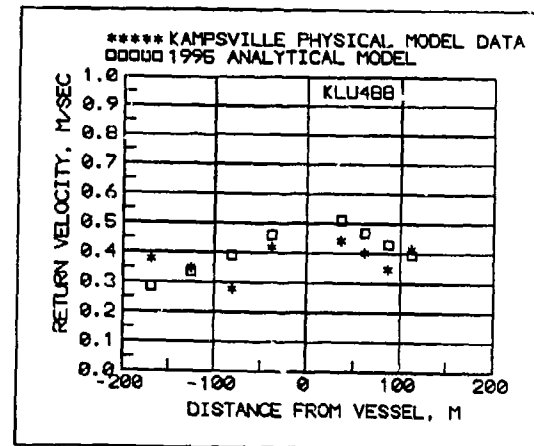
b. Test KLU488
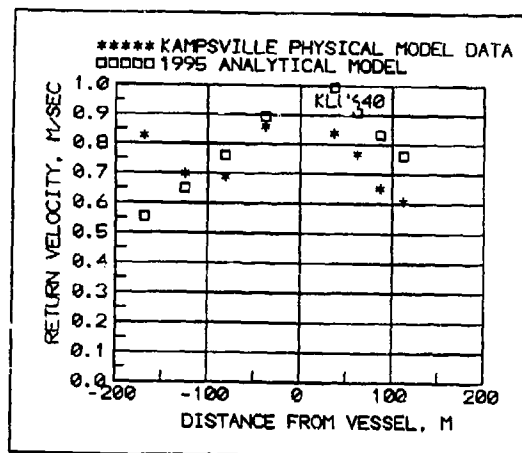
c. Test KLU640
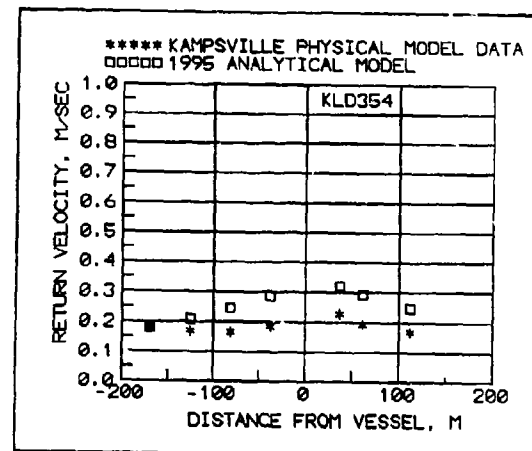
d. Test KLD354

Figure 9. Observed Kampsville physical model return velocity versus computed return velocity using 1995 analytical method for individual tests: KLU335, 488, 640, 354 and KLD506 and 659 (Continued)
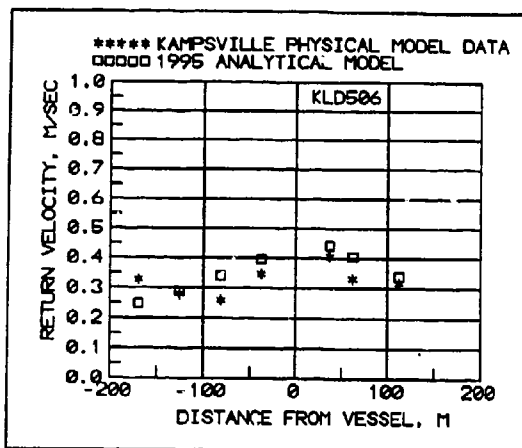
e. Test KLD506

F. Test KLD659

Figure 9. (Concluded)
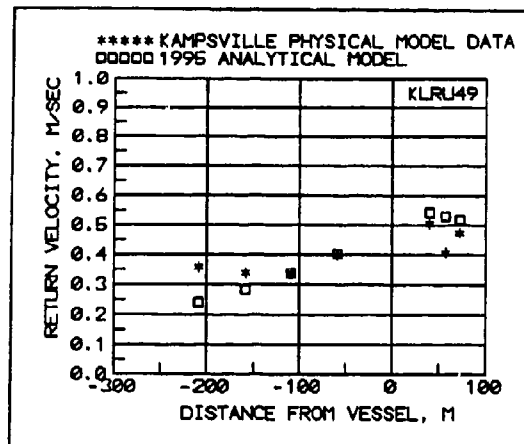
a. Test KLRU49
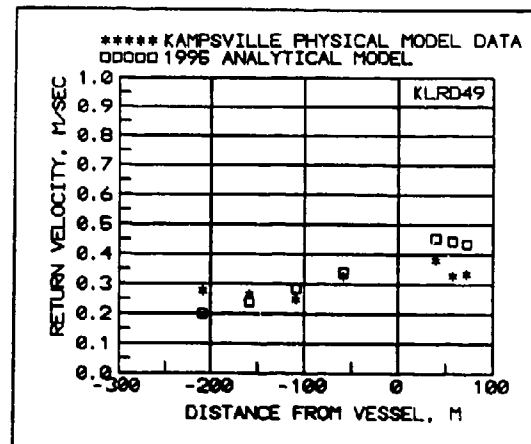
b. Test KLRD49
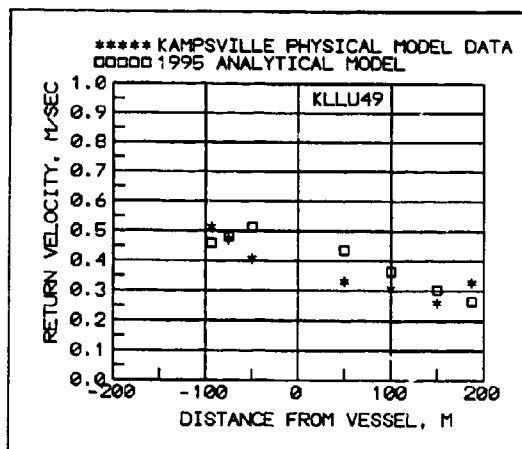
c. Test KLLU49
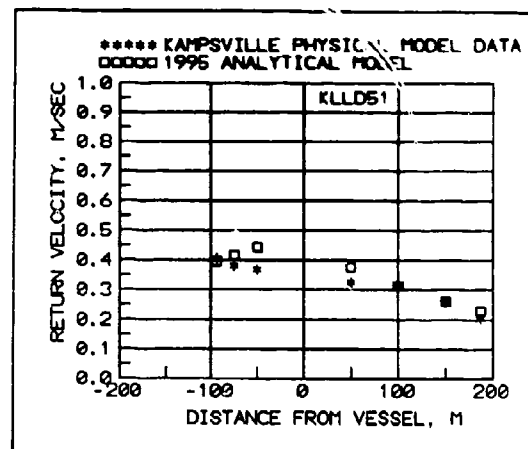
d. Test KLLD51

Figure 10. Observed Kampsville physical model return velocity versus computed return velocity using 1995 analytical method for individual tests: KLRU49, KLRD49, KLLU49, KLLD51, KL1U46, and KL1U61 (Continued)
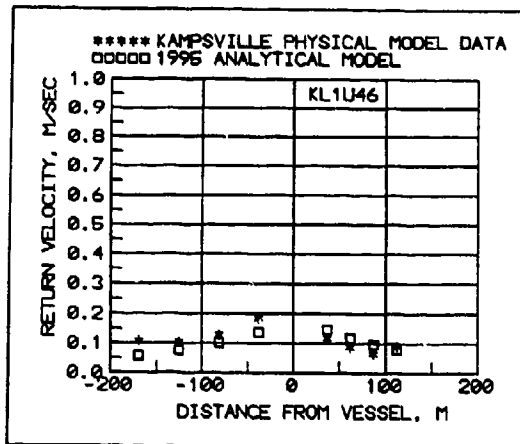
e. Test KL1U46

F. Test KL1U61

Figure 10. (Concluded)
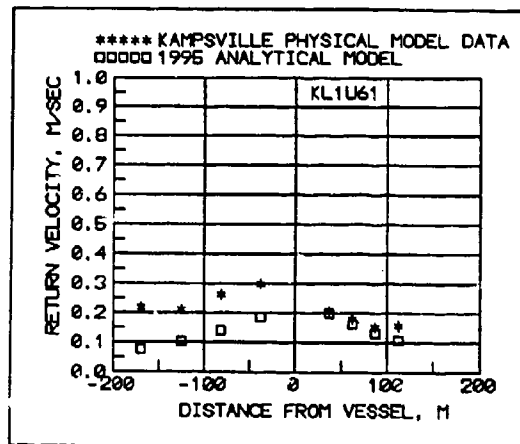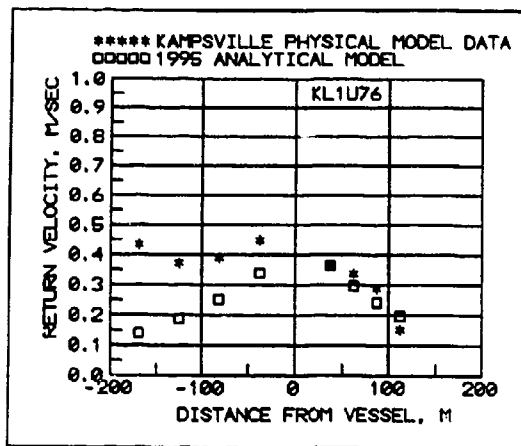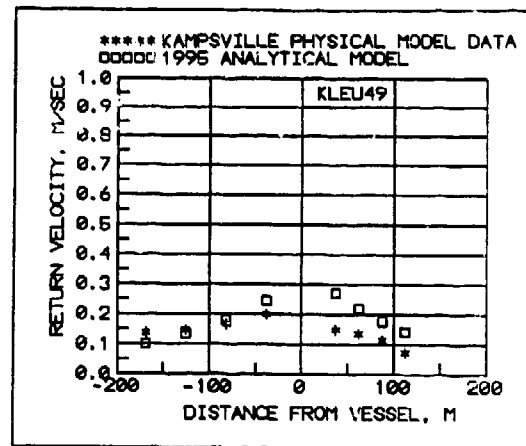
a. Test KL1U76

b. Test KLEU49
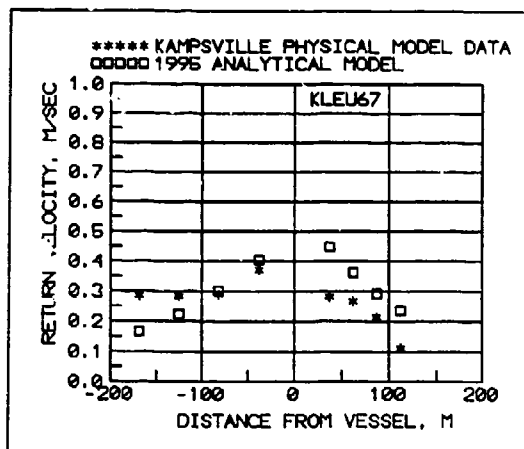
c. Test KLEU67
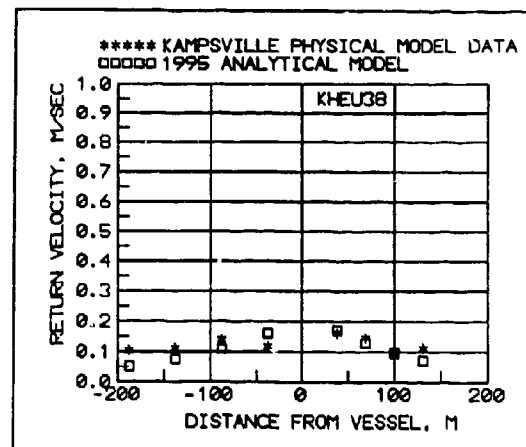
d. Test KHEU38

Figure 5. Observed Kampsville physical model return velocity versus computed return velocity using 1995 analytical method for individual tests: KL1U76, KLEU49, KLEU67, KHEU38, KHEU56, and KHOU38 (Continued)
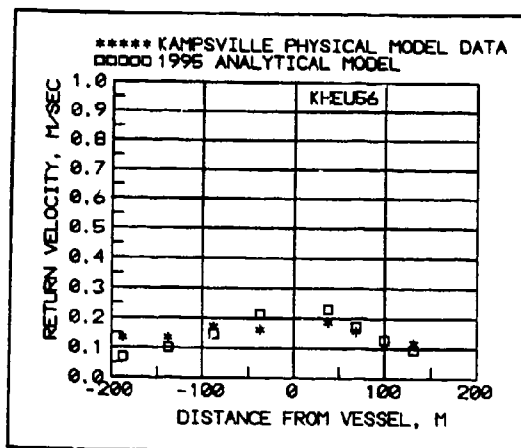
e. Test KHEU56
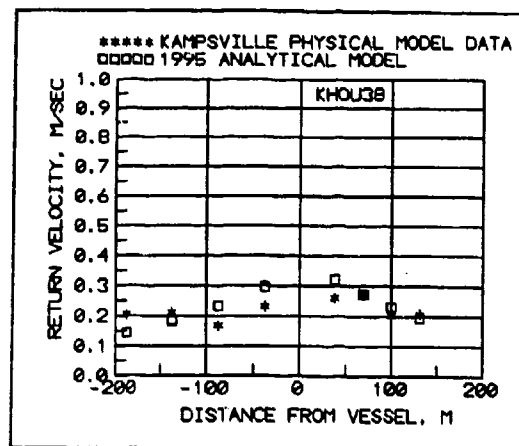
f. Test KHOU38

Figure 11. (Concluded)
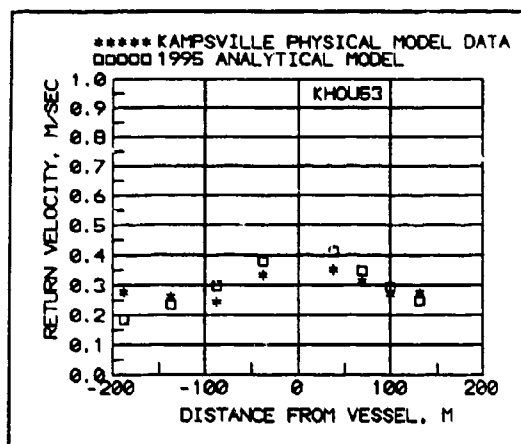
a. Test KHOU53
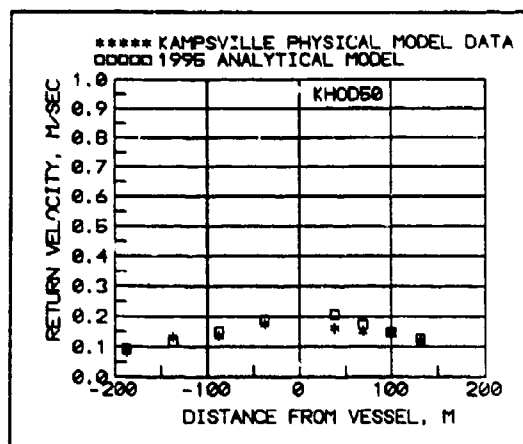
b. Test KHOD50
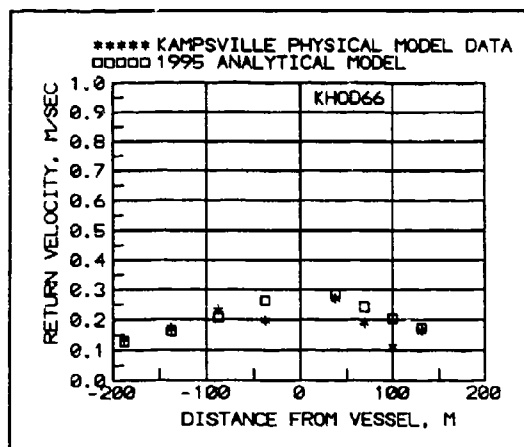
c. Test KHOD66
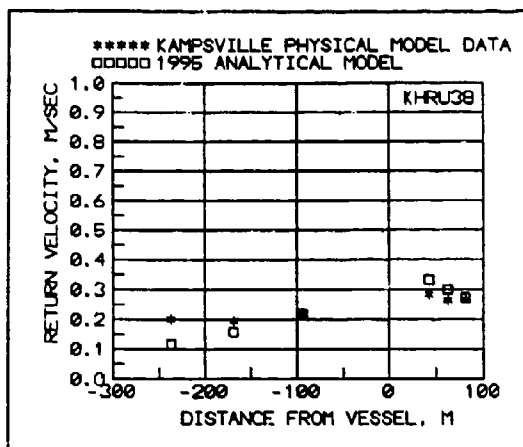
d. Test KHRU38

Figure 12. Observed Kampsville physical model return velocity versus computed return
velocity using 1995 analytical method for individual tests: KHOU53, KHOD50,
KHOD66, KHRU38, KHRD66, and KHLU38 (Continued)
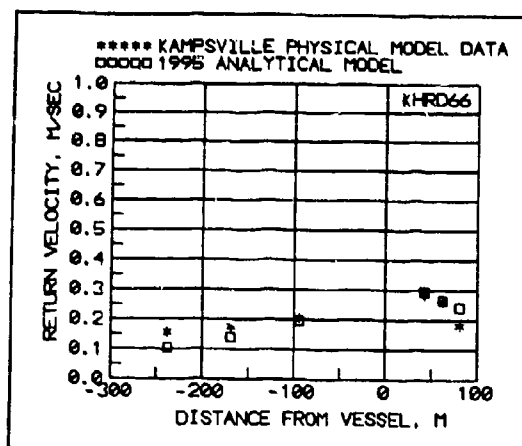
e. Test KHRD66
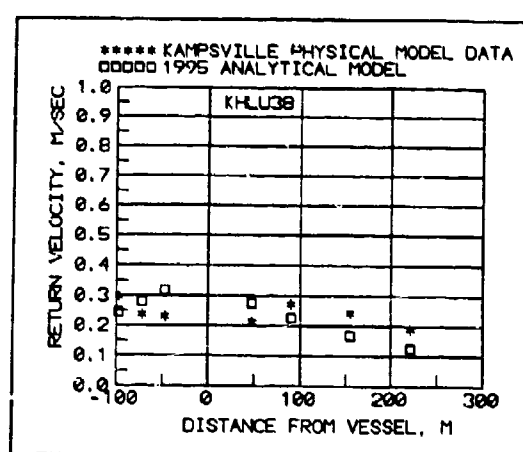
f. Test KHLU38

Figure 12. (Concluded)
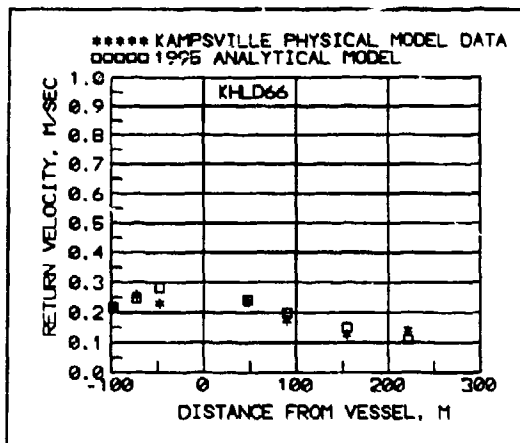
a. Test KHLD66
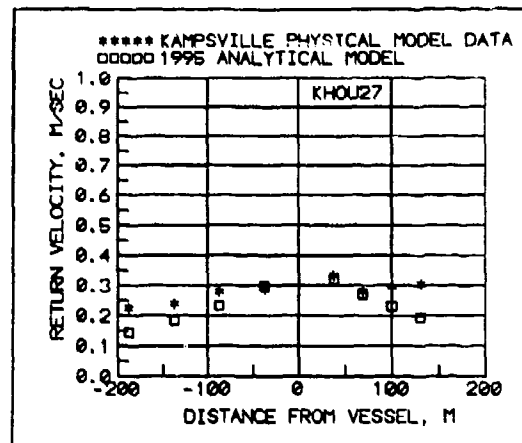
b. Test KHOU27
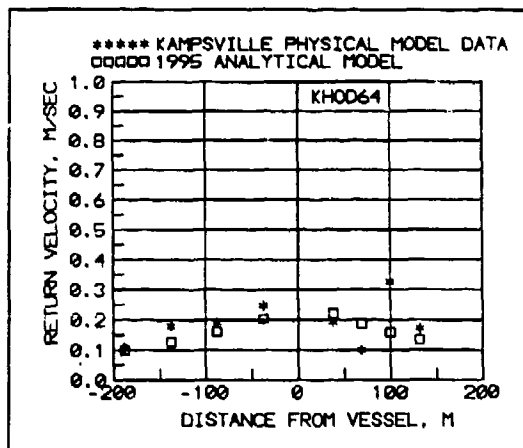
c. Test KHOD64
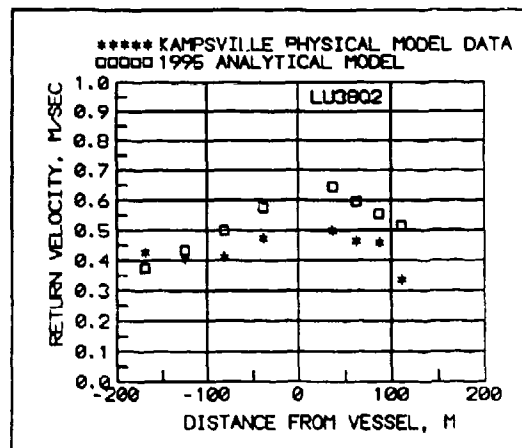
d. Test LU38Q2

Figure 13. Observed Kampsville physical model return velocity versus computed return velocity using 1995 analytical method for individual tests: KHLD66, KHOU27, KHOD64, LU38Q2, and LD58Q2 (Continued)
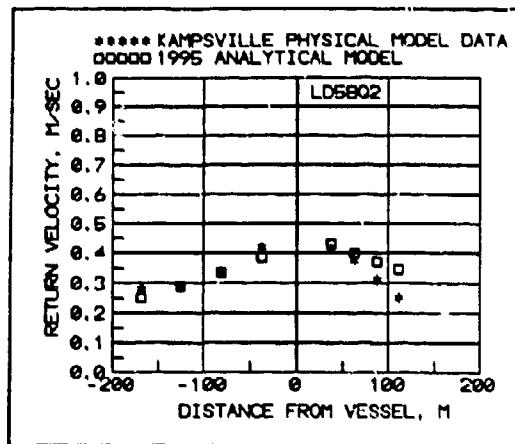
e. Test LD58Q2

Figure 13. (Concluded)

Table 1
Physical Model Experimental Conditions

Test Number	Vessel Beam, m	Total Length of Barges, m	Effective Draft, m	Vessel Power, Hp	Vessel Speed Relative to Ground, m/sec	Ambient Velocity, m/sec	Direction, 1 = Upbound 2 = Downbound	Channel Area Left of Vessel, m²	Distance from Left Bank to Vessel m	Total Channel Area, m²	Total Channel Width, m
KLU335	32.00	297.3	2.85	5600.	1.67	0.175	1.	617.3	186.0	1032.5	315.0
KLU488	32.00	297.3	2.81	5600.	2.43	0.175	1.	617.3	186.0	1032.5	315.0
KLU640	32.00	297.3	2.78	5600.	3.18	0.175		617.3	186.0	1032.5	315.0
KLD354	32.00	297.3	2.86	5600.	1.79	0.175	-1.	617.3	186.0	1032.5	315.0
KLD506	32.00	297.3	2.82	5600.	2.50	0.175	-1.	617.3	186.0	1032.5	315.0
KLD659	32.00	297.3	2.79	5600.	3.32	0.175	-1.	617.3	186.0	1032.5	315.0
KLRU49	32.00	297.3	2.81	5600.	2.43	0.175	1.	775.4	228.0	1032.5	315.0
KLRD49	32.00	297.3	2.83	5600.	2.43	0.175	-1.	775.4	228.0	1032.5	315.0
KLLU49	32.00	297.3	2.92	5600.	2.45	0.175	1.	324.2	111.0	1032.5	315.0
KLLD51	32.00	297.3	2.83	5600.	2.52	0.175	-1.	324.2	111.0	1032.5	315.0
KL1U46	10.67	178.4	2.65	5600.	2.28	0.175	1.	617.3	186.0	1032.5	315.0
KL1U61	10.67	178.4	2.63	5600.	3.03	0.175	1.	617.3	186.0	1032.5	315.0
KL1U76	10.67	178.4	2.61	5600.	3.81	0.175	1.	617.3	186.0	1032.5	315.0
KLEU49	32.00	297.3	1.14	5600.	2.43	0.175	1.	617.3	186.0	1032.5	315.0
KLEU67	32.00	297.3	1.14	5600.	3.34	0.175	1.	617.3	186.0	1032.5	315.0
KHEU38	32.00	297.3	1.15	5600.	1.91	0.71	1.	1075.6	209.9	1817.0	362.4
KHEU56	32.00	297.3	1.12	5600.	2.82	0.71	1.	1075.6	209.9	1817.0	362.4
KHOU38	32.00	297.3	2.83	5600.	1.91	0.71	1.	1075.6	209.9	1817.0	362.4
KHOU53	32.00	297.3	2.79	5600.	2.67	0.71	1.	1075.6	209.9	1817.0	362.4

(Continued)

Table 1 (Concluded)

| Test Number	Vessel Beam, m	Total Length of Barges, m	Effective Draft, m	Vessel Power, Hp	Vessel Speed Relative to Ground, m/sec	Ambient Velocity, m/sec	Direction, 1=Upbound 2=Downbound	Channel Area Left of Vessel, m²	Distance from Left Bank to Vessel m	Total Channel Area, m²	Total Channel Width, m
KHOD50	32.00	297.3	2.87	5600.	2.52	0.71	-1.	1075.6	209.9	1817.0	362.4
KHOD66	32.00	297.3	2.83	5600.	3.28	0.71	-1.	1075.6	209.9	1817.0	362.4
KHRU38	32.00	297.3	2.82	5600.	1.91	0.71	1.	1387.7	259.9	1817.0	362.4
KHRD66	32.00	297.3	2.82	5600.	3.28	0.71	-1.	1387.7	259.9	1817.0	362.4
KHLU38	32.00	297.3	2.82	5600.	1.91	0.71	1.	516.2	119.8	1817.0	362.4
KHLD66	32.00	297.3	2.82	5600.	3.28	0.71	-1.	516.2	119.8	1817.0	362.4
KHOU27	32.00	297.3	2.83	5600.	1.37	1.152	1.	1075.6	209.9	1817.0	362.4
KHOD64	32.00	297.3	2.86	5600.	3.20	1.152	-1.	1075.6	209.9	1817.0	362.4
LU38Q2	32.00	237.8	2.73	5600.	1.90	0.694	1.	536.9	181.2	900.0	306.2
LD58Q2	32.00	237.8	2.75	5600.	2.90	0.694	-1.	536.9	181.2	900.0	306.2

32
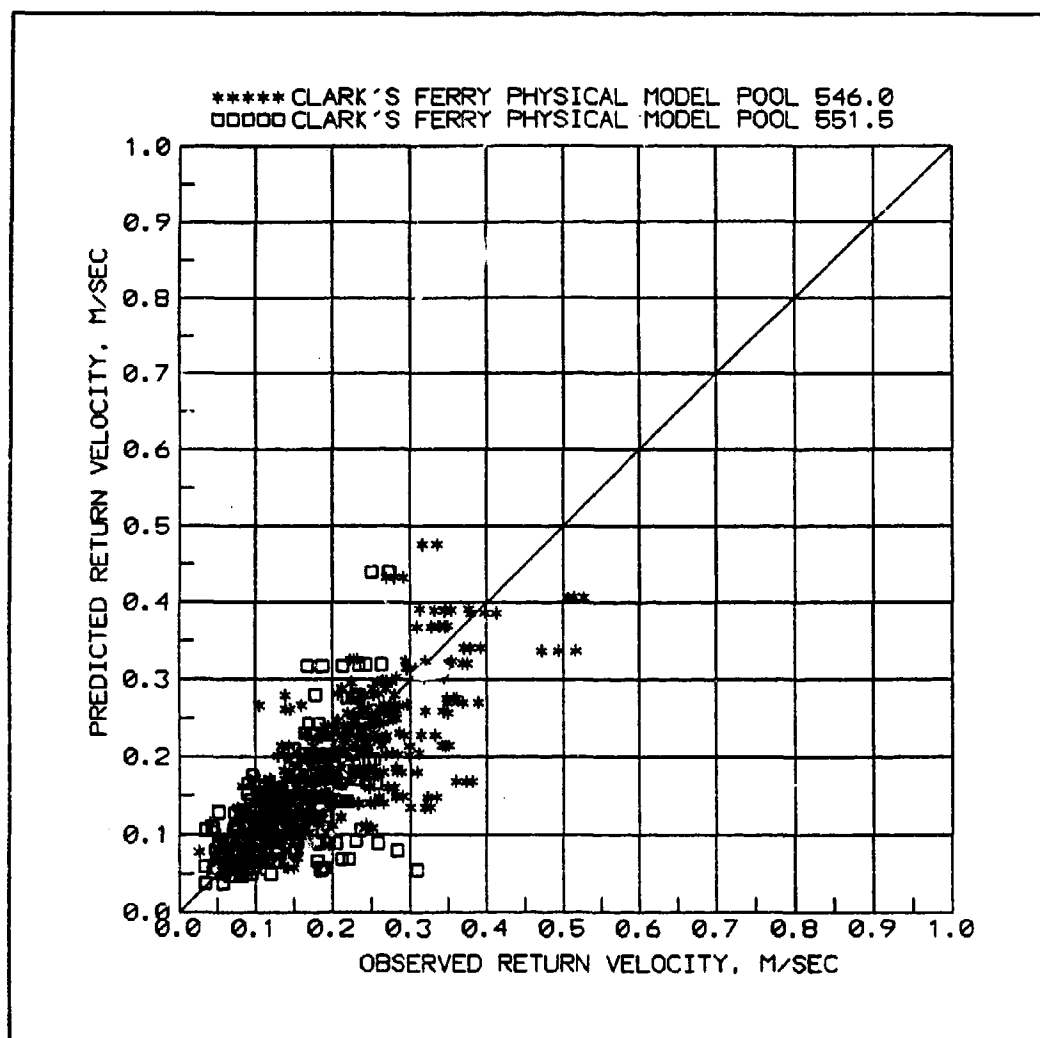
Figure 14. Observed Clark's Ferry physical model return velocity versus computed return velocity using 1995 analytical method for N < 52
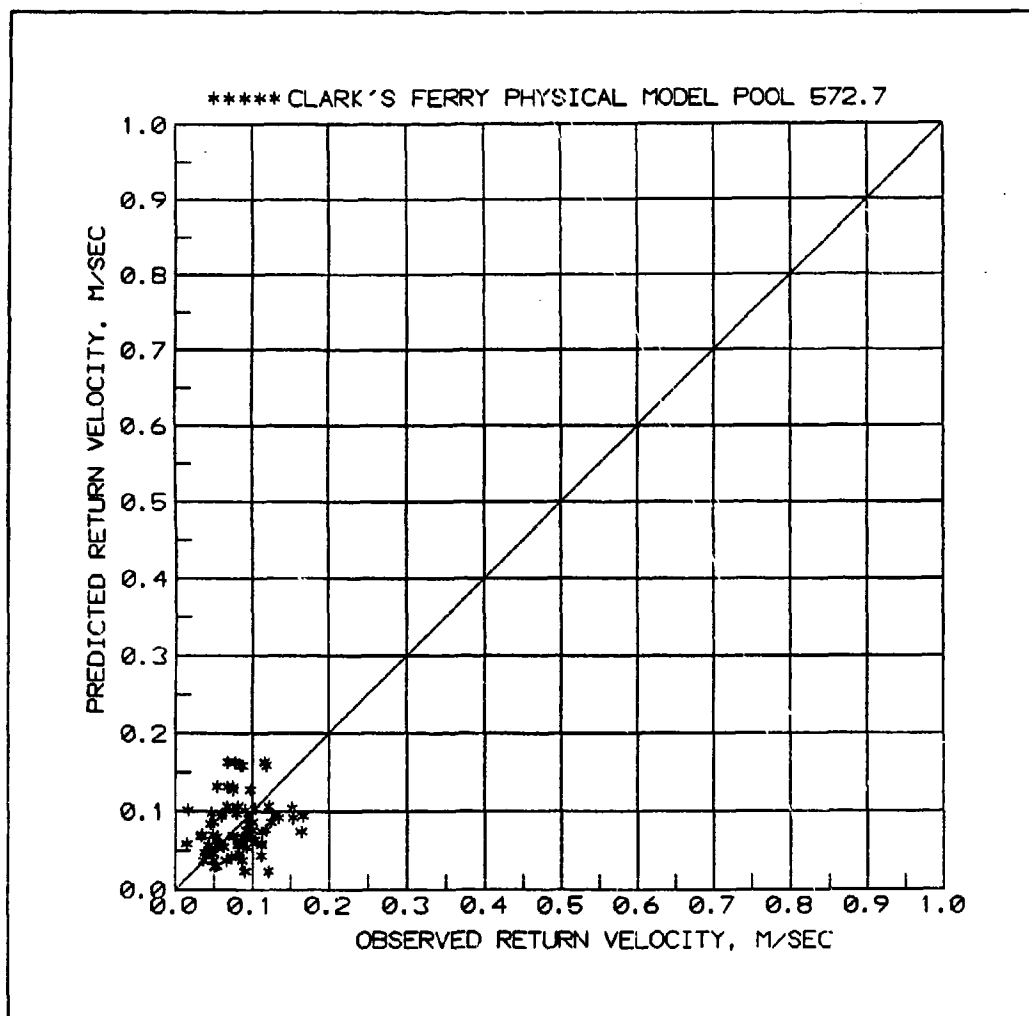
Figure 15. Observed Clark's Ferry physical model return velocity versus computed return velocity using 1995 analytical method for N = 85
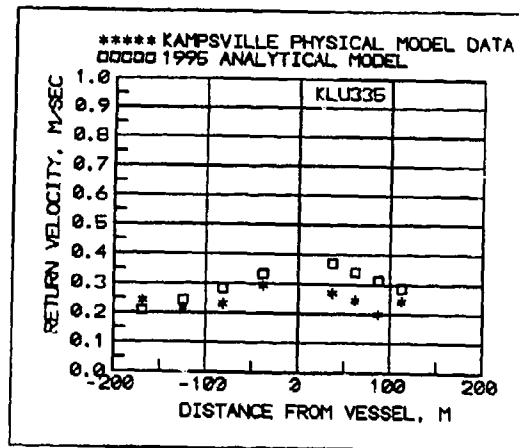
Figure 16. Observed Kampsville prototype return velocity versus computed return velocity using 1995 analytical method

Figure 17. Observed Clark's Ferry prototype return velocity versus computed return velocity using 1995 analytical method

a. M/V Mr. Aldo
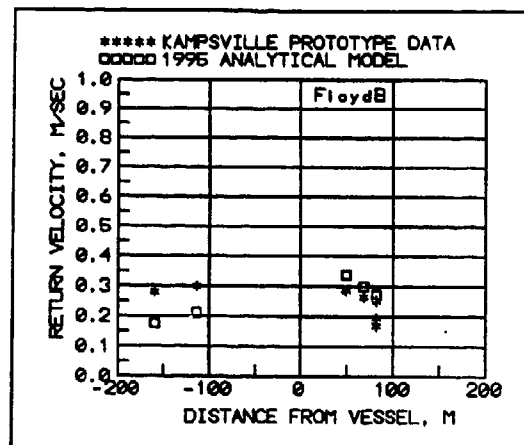
b. M/V Floyd Blaske
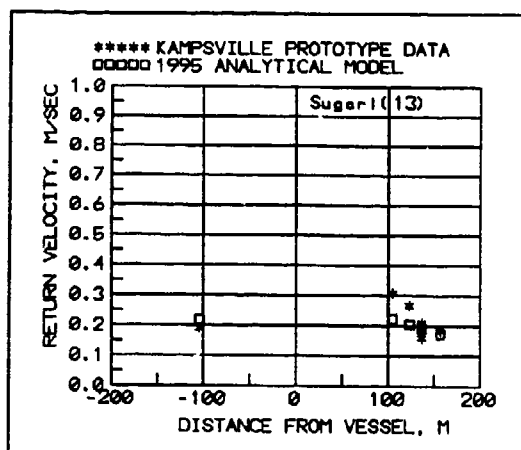
c. M/V Sugarl (13)
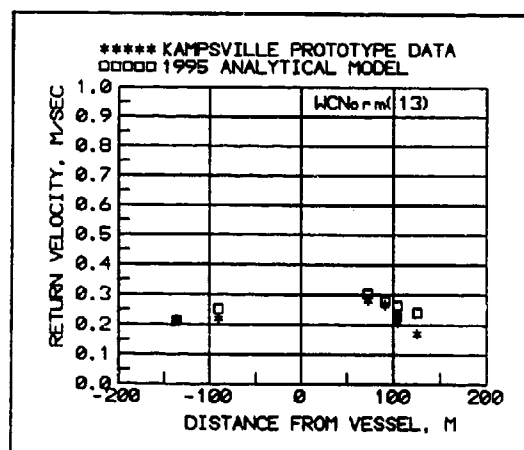
d. M/V W. C. Norman (13)

Figure 18. Observed Kampsville prototype return velocity versus computed return velocity using 1995 analytical method for individual tests: M/V Mr. Abdo, Floyd Blaske, Sugar (13), W. C. Norman (13), ContiKarla, and Rambler (Continued)
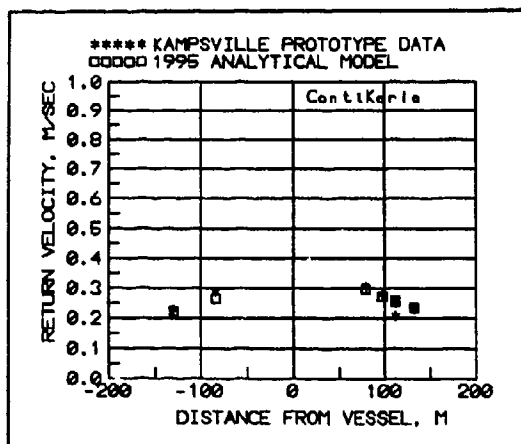
e. M/V Conti Karla
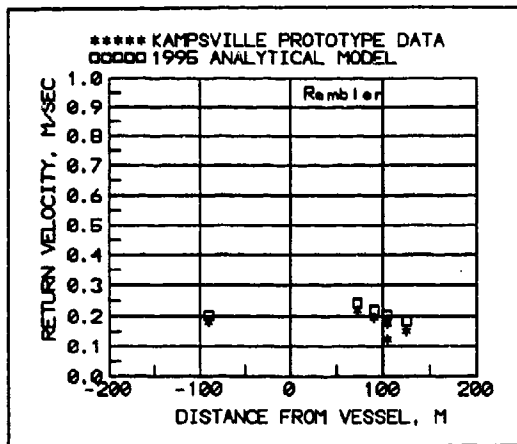
f. M/V Rambler

Figure 18. (Concluded)
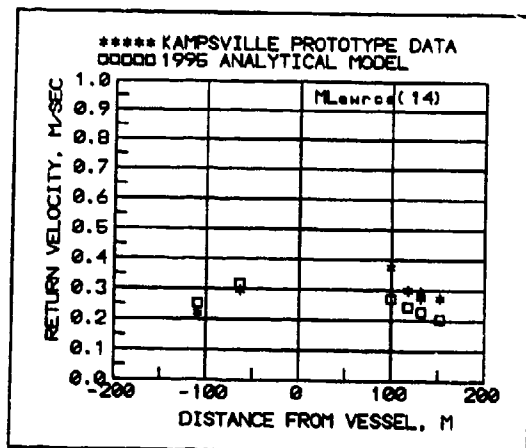
a. M/V Mlawrce (14)
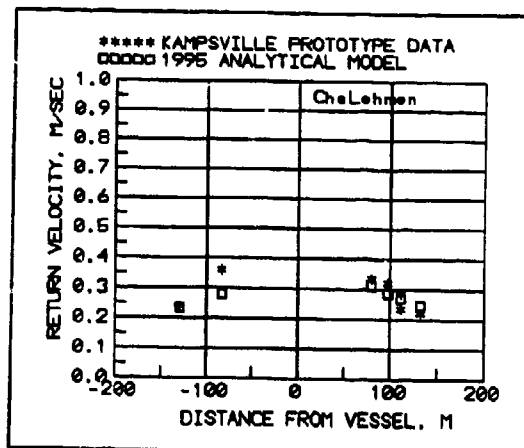
b. M/V ChaLehman
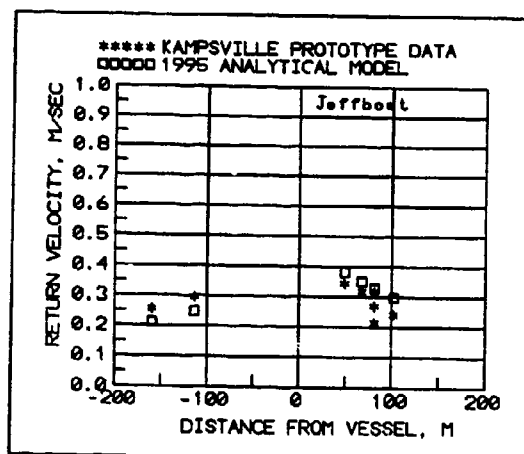
c. Jeffboat
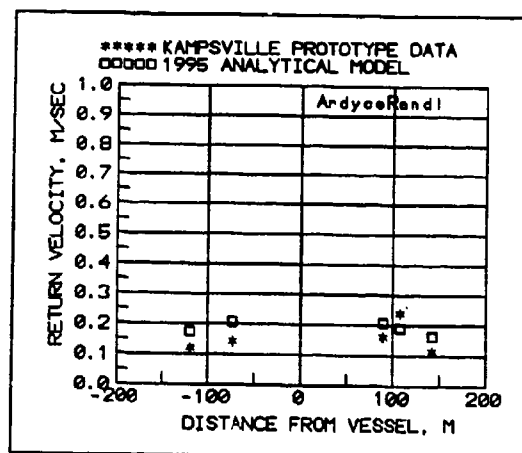
d. M/V Ardyce Randl

Figure 19. Observed Kampsville prototype return velocity versus computed return velocity
using 1995 analytical method for individual tests: M/V Mlawrce, ChaLehman,
Jeffboat, Ardyce Randl, Mr. Paul (15), and Marget 0 (15) (Continued)
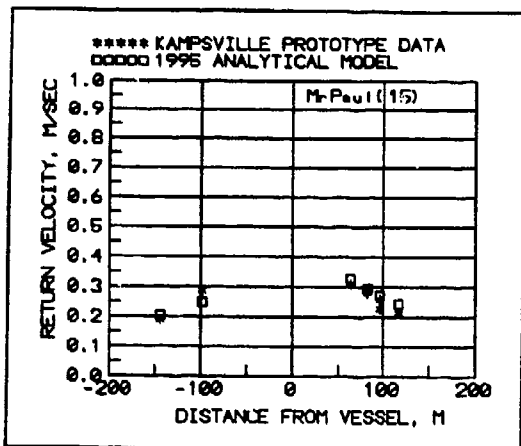
e. M/V Mr. Paul (15)
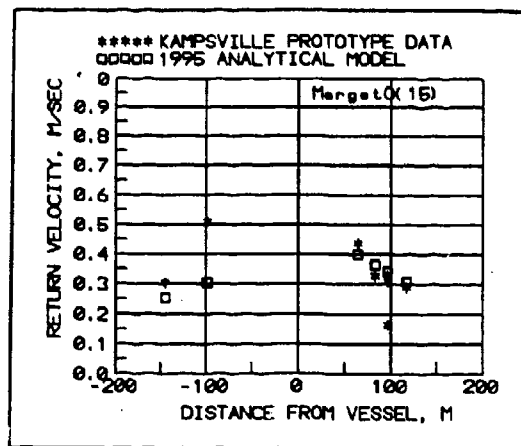
f. M/V Marget O (15)

Figure 19. (Concluded)
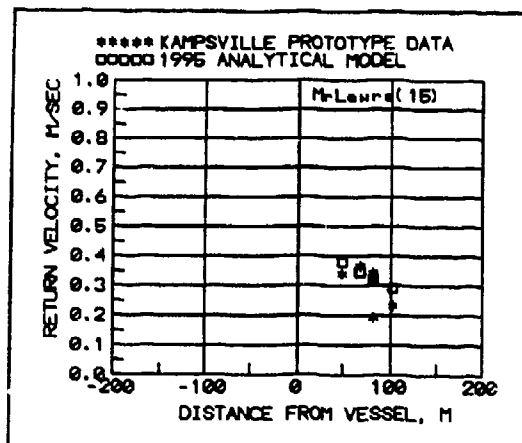
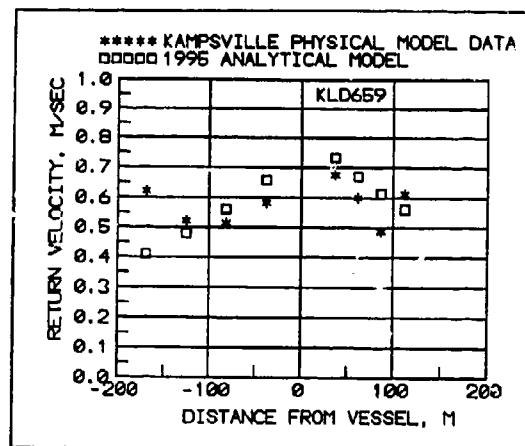a. M/V Mr. Lawre (15)
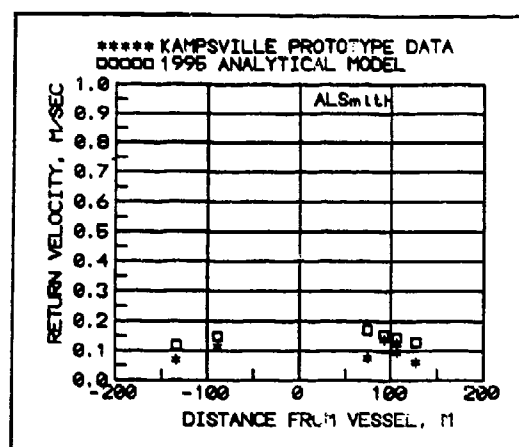
b. M/V Al Smith
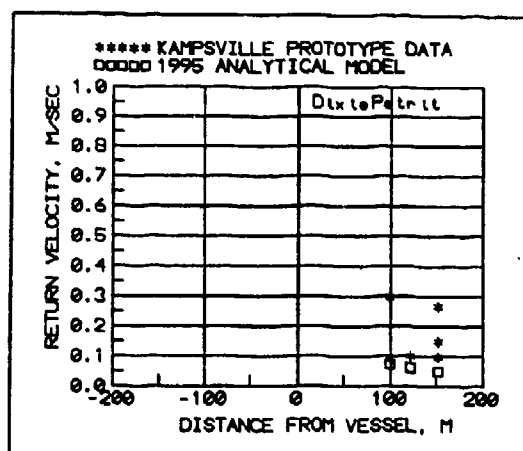
c. M/V Dixie Patrit
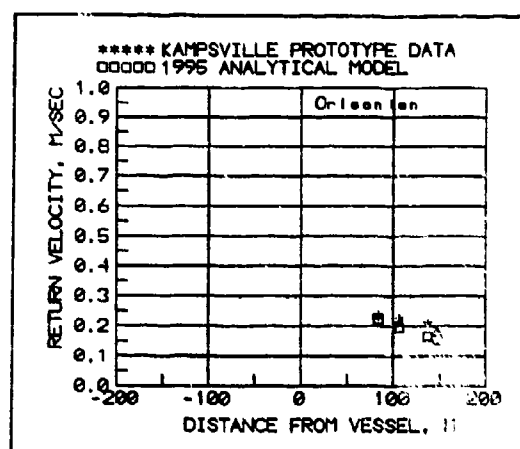
d. M/V Orleanian

Figure 20. Observed Kampsville prototype return velocity versus computed return velocity using 1995 analytical method for individual tests: M/V Mr. Lawre (15), Al Smith, Dixie Patrit, Orleanian, Pat Breen, and Dixie Expre 1 (Continued)
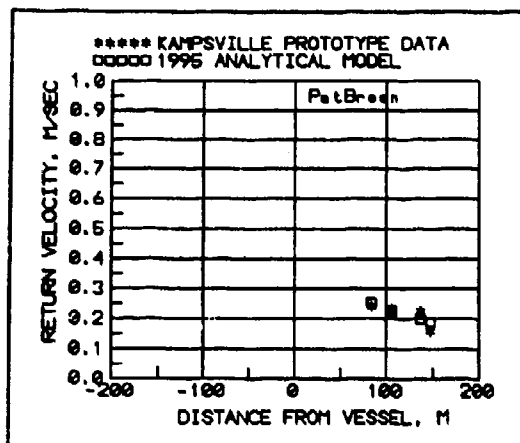
e. M/V Pat Breen
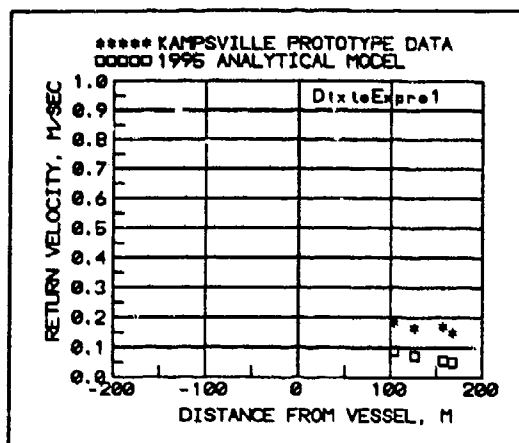
f. M/V Dixie Expre 1

Figure 20. (Concluded)
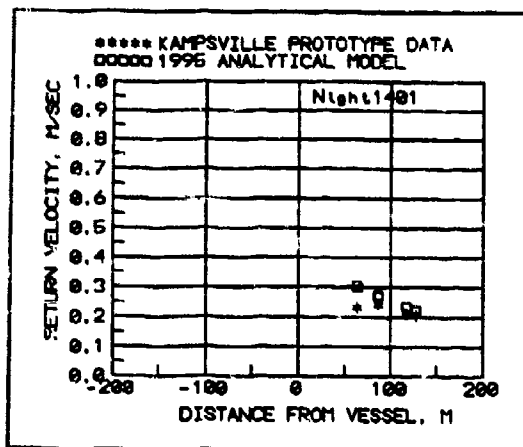
a. M/V Night 1401
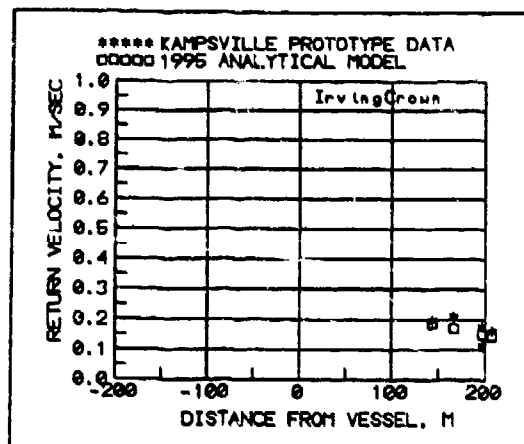
b. M/V Irving Crown
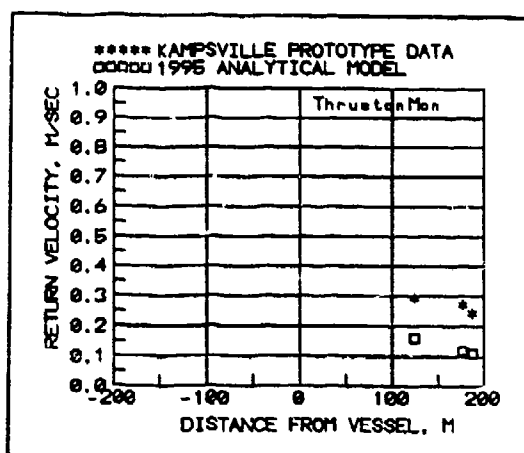
c. M/V Thurston Mon
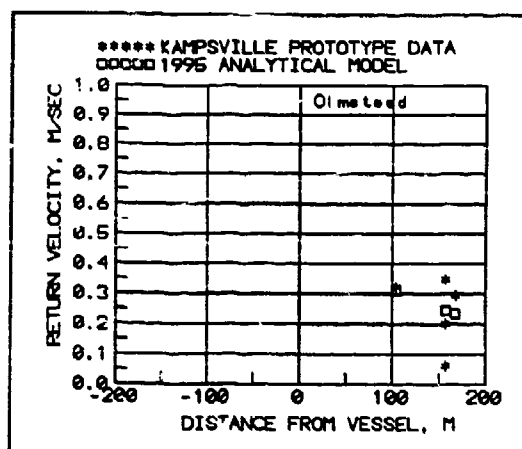
d. M/V Olmstead

Figure 21. Observed Kampsville prototype return velocity versus computed return velocity
using 1995 analytical method for individual tests: M/V Night 1401, Irving Crown,
Thurston Mon, Olmstead, Jack D. Wofford, and Dixie Expre 2 (Continued)
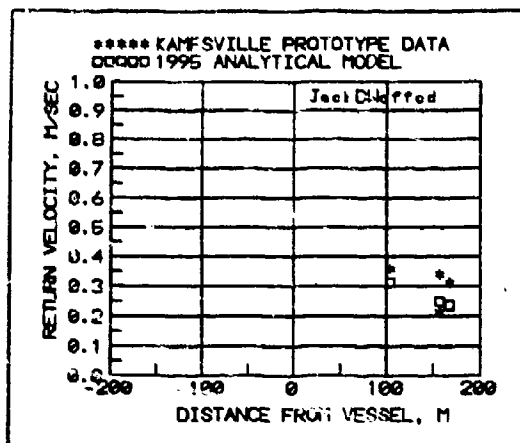
e. M/V Jack D. Woffod
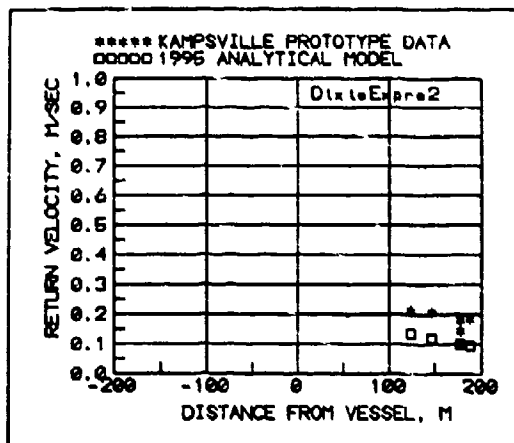
f. M/V Dixie Expre 2

Figure 21. (Concluded)

Table 2
Kampsville Prototype Experimental Conditions

| Test Number	Vessel Beam, m	Total Length of Barges, m	Effective Draft, m	Vessel Power, Hp	Vessel Speed Relative to Ground, m/sec	Ambient Velocity, m/sec	Direction, 1 = Upbound 2 = Downbound	Channel Area Left of Vessel, m²	Distance from Left Bank to Vessel m	Total Channel Area, m²	Total Channel Width, m
MrAldo	32.00	297.3	2.74	5600.	2.78	0.45	-1.	783.6	230.0	1244.4	355.1
FloydBlaske	32.00	237.8	2.03	5000.	2.18	0.45	1.	816.3	245.0	1244.4	355.1
Sugarll(13)	32.00	237.8	2.29	3375.	1.88	0.49	1.	705.7	190.0	1309.1	358.8
WCNorm(13)	32.00	237.8	2.74	1800.	2.90	0.49	-1.	800.2	222.0	1309.1	358.8
ContiKarla	32.00	297.3	2.74	3060.	1.70	0.49	1.	775.0	215.0	1309.1	358.8
Rambler	32.00	237.8	2.74	2000.	2.48	0.54	-1.	718.5	222.0	1320.0	359.4
MLawrce(14)	32.00	237.8	2.03	5600.	2.56	0.54	1.	711.9	195.0	1320.0	359.4
ChaLehmen	32.00	237.8	2.74	5600.	1.85	0.54	1.	784.8	215.0	1320.0	359.4
Jeffbost	32.00	297.5	2.74	6000.	1.84	0.54	1.	875.0	245.0	1320.0	359.4
ArdyceRandl	32.00	297.5	2.74	5600.	2.36	0.56	-1.	737.7	205.0	1331.0	360.0
MrPaul(15)	32.00	178.4	2.27	5600.	2.25	0.56	1.	840.7	230.0	1331.0	360.0
MargetO(15)	32.00	178.4	2.51	5600.	3.83	0.56	-1.	840.7	230.0	1331.0	360.0
MrLawre(15)	32.00	297.5	2.74	5600.	3.16	0.56	-1.	862.7	245.0	1331.0	360.0
ALSmith	21.34	237.8	2.74	1800.	2.80	0.57	-1.	868.9	220.0	1342.0	360.6
DixiePatri	10.67	178.4	2.74	3200.	2.48	0.29	-1.	424.5	145.0	1118.9	320.0
Orleanizn	32.00	237.8	2.03	4300.	2.02	0.29	1.	484.5	160.0	1118.9	320.0
PatBreen	32.00	297.3	2.74	5600.	2.29	0.29	-1.	484.5	160.0	1118.9	320.0
DixieExpre1	15.90	160.0	1.52	1700.	3.40	0.29	-1.	404.7	140.0	1118.9	320.0
Night1401	32.00	237.8	2.74	9999.	1.62	0.29	1.	560.8	180.0	1118.9	320.0

(Continued)

Table 2 (Concluded)

Test Number	Vessel Beam, m	Total Length of Barges, m	Effective Draft, m	Vessel Power, Hp	Vessel Speed Relative to Ground, m/sec	Ambient Velocity, m/sec	Direction, 1 = Upbound 2 = Downbound	Channel Area Left of Vessel, m²	Distance from Left Bank to Vessel m	Total Channel Area, m²	Total Channel Width, m
IrvingCrown	32.00	178.4	2.74	2400.	1.59	0.29	1.	254.6	100.0	1118.9	320.0
ThrustonMon	32.00	237.8	1.63	4200.	2.18	0.29	1.	327.9	120.0	1118.9	320.0
Olmstead	32.00	297.3	2.74	5920.	2.19	0.29	1.	404.7	140.0	1118.9	320.0
JackDWoffod	32.00	297.3	2.74	5000.	2.22	0.29	1.	404.7	140.0	1118.9	320.0
DixieExpre2	15.90	160.9	2.74	1800.	2.58	0.29	1.	327.9	120.0	1118.9	320.0

5 Development of 1995 Analytical Method for Prediction of Water-Level Drawdown

To compute water-level drawdown at position Y from the center line of the vessel, the average return velocity, as determined from Equation 13, was used in Equation 2 to determine the average drawdown z for the section. The difficulty at this point is that the number of drawdown distributions in the physical model was limited. Therefore, return velocity distributions were used to determine how the drawdown varied on either side of the tow and across the section. The drawdown on either side of the tow was determined from the same equations used for return velocity in Equations 14 and 15. For B_{side}/B_{total} from 0 to 0.5

$$\frac{Z_{rs}}{z} = 1.65 - 1.3\frac{B_{side}}{B_{total}} \tag{18}$$

For B_{side}/B_{total} from 0.5 to 1.0

$$\frac{Z_{rs}}{z} = 1.35 - 0.7\frac{B_{side}}{B_{total}} \tag{19}$$

The maximum drawdown at $(Y-B)/(B_{side}-B) = 0$ is

$$\frac{Z_{sm}}{Z_{ts}} = \alpha_{draw} \tag{20}$$

where α_{draw} is a function of α' defined by Equation 16.

The distribution of Z(Y) is defined as

$$\frac{Z(Y)}{Z_{sm}} = \exp\left[C\left(\frac{Y-B}{B_{side}-B}\right)\right] \tag{21}$$

where $Z_t(Y)$ is the maximum water-level drawdown during the tow event at distance Y from the vessel center line and C is defined by Equation 17. α_{draw} is the primary factor that establishes the slope of the drawdown distribution. Based on the Kampsville and Clark's Ferry physical model drawdown data and detailed drawdown measurements for the WC Norman tow in the Kampsville physical model, α_{draw} is defined by

$$\alpha_{draw} = \alpha'^{\ 0.5} \tag{22}$$

Scatterplots of observed physical model drawdown from Kampsville and Clark's Ferry versus computed drawdown using the 1995 analytical drawdown method are shown in Figures 22 and 23, respectively. Comparison of the analytical method with detailed drawdown data from the WC Norman tow in the Kampsville physical model is shown in Table 3. The physical model-based 1995 Analytical Drawdown method was then tested for agreement with the prototype data which was taken at a single-wave gauge at the Kampsville site on the Illinois River. The wave data from ISWS were collected at 10 samples/sec. To be consistent with the return velocity analysis, an 11-sec moving average was used to smooth the wave data before extracting the ambient and changed water level from the record. Drawdown measurements based on only a staff gage reading were not used in this comparison. A scatterplot of drawdown for the ISWS prototype data is shown in Figure 24.

48
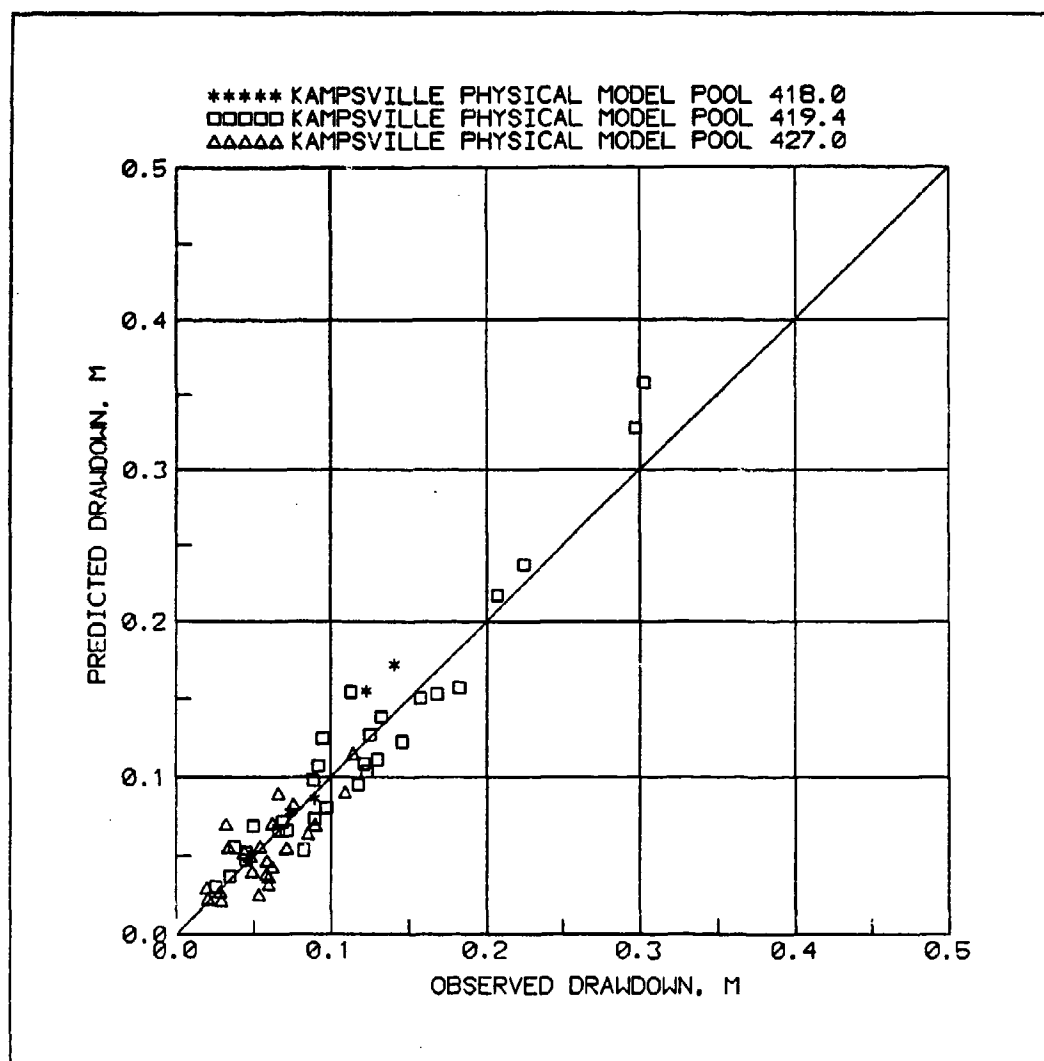
Figure 22. Observed Kampsville physical model drawdown versus computed drawdown using 1995 analytical method
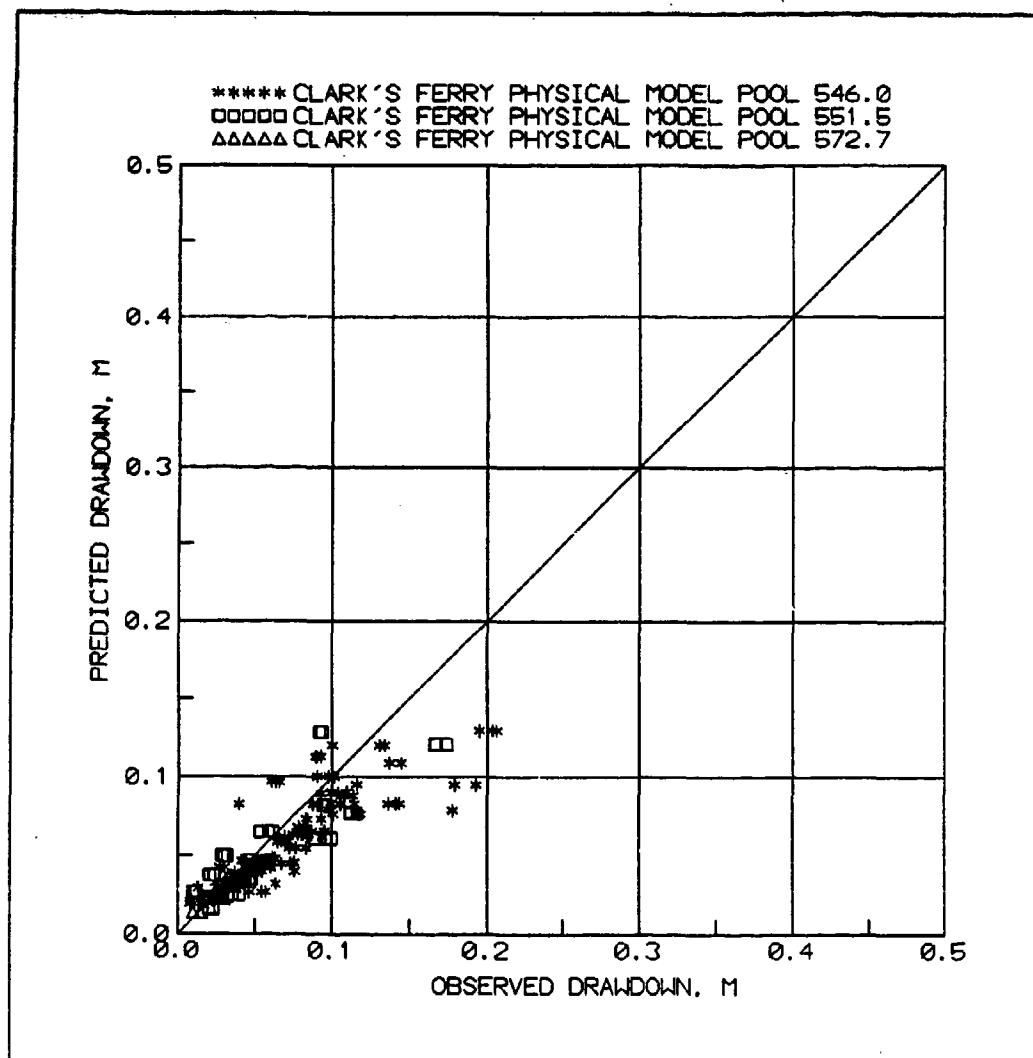
Figure 23. Observed Clark's Ferry physical model drawdown versus computed drawdown using 1995 analytical method

Chapter 5   Development of 1995 Anlaytical Method for Prediction

Table 3
Observed Versus Computed Drawdown for WC Norman Test

Distance from tow, m	-162	-100	-41	34	70	106	124
Observed phys model, cm[1]	5.4	5.5	6.8	7.7	6.8	6.9	-
Observed Prototype, cm[1]	-	-	-	-	-	-	7.2
Computed drawdown, cm[1]	5.4	6.1	6.9	8.4	7.7	7.2	6.9

Note: (-) No value was available.
[1] These values are drawdown.
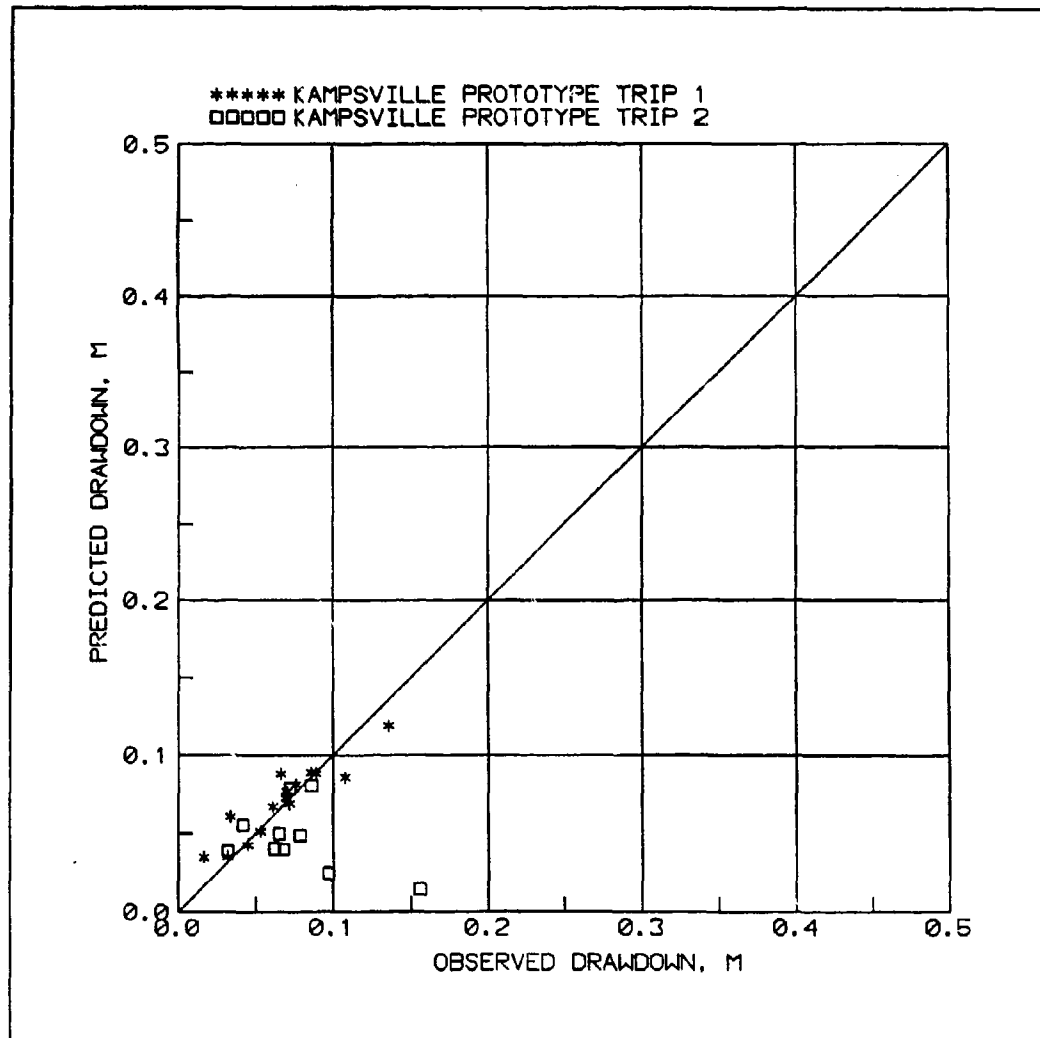
Figure 24. Observed Kampsville prototype drawdown versus computed drawdown using 1995 analytical method

6 Comparison of 1995 Analytical Method with Independent Field Data

Since the Kampsville and Clark's Ferry field data were used to verify the Kampsville and Clark's Ferry physical models which were then used to produce data used in the development of the 1995 method, comparison of the analytical method to the same field data is not independent. Two field data sets were used to provide an independent comparison with the 1995 analytical method. The first data set was return velocity data taken by ESE (1981) at one section on the Mississippi River and one on the Illinois River. A scatterplot of all ESE return velocity data meeting the limitations of the 1995 method is shown in Figure 25. The second data set comes from data collected at four sites on the Ohio River by the U.S. Army Engineer District, Louisville, whose cross sections are shown in Figures 26 through 29 and data on Tables 4 through 7. Scatterplots for all four sections are shown in Figures 30 and 31 for return velocity and drawdown, respectively. Scatter is large, but the trend around the line of perfect agreement is correct for all three scatterplots.
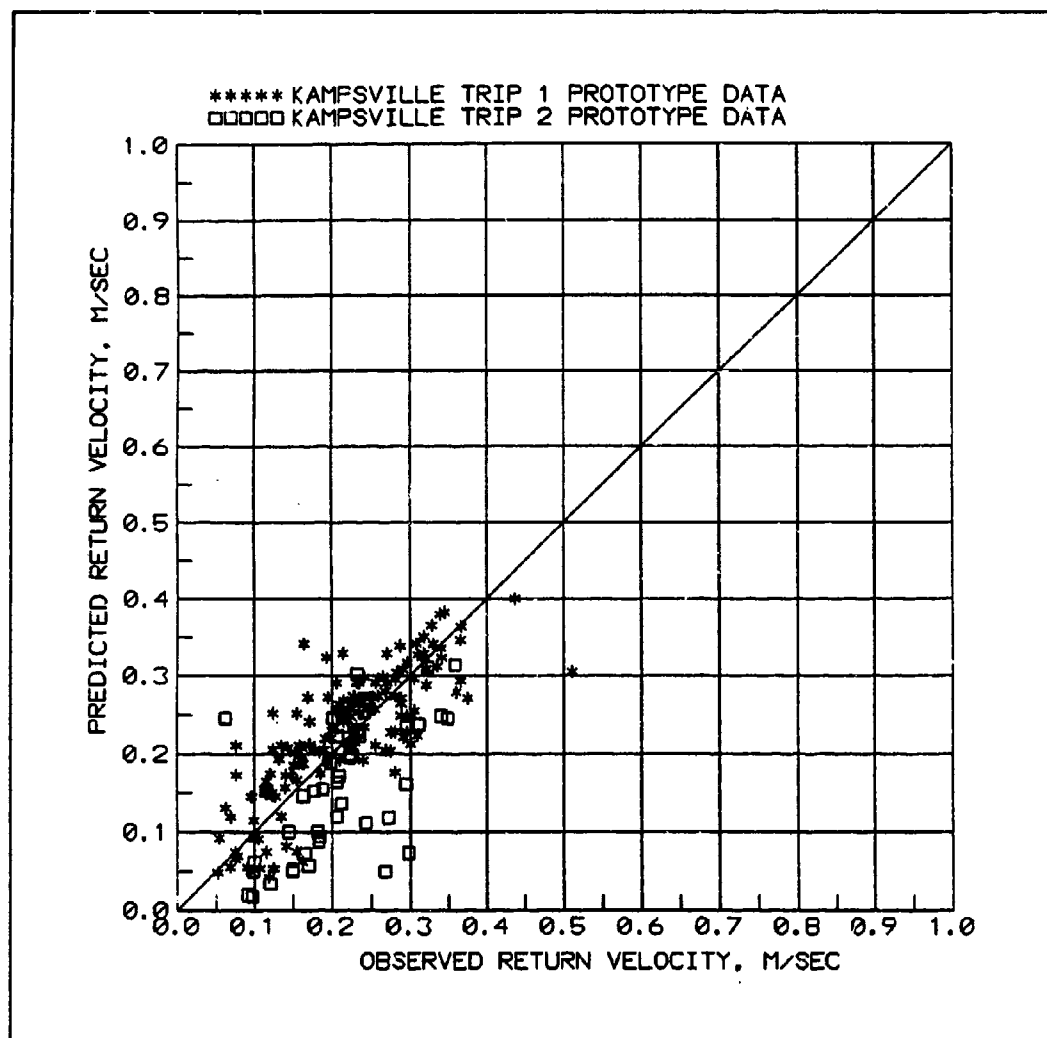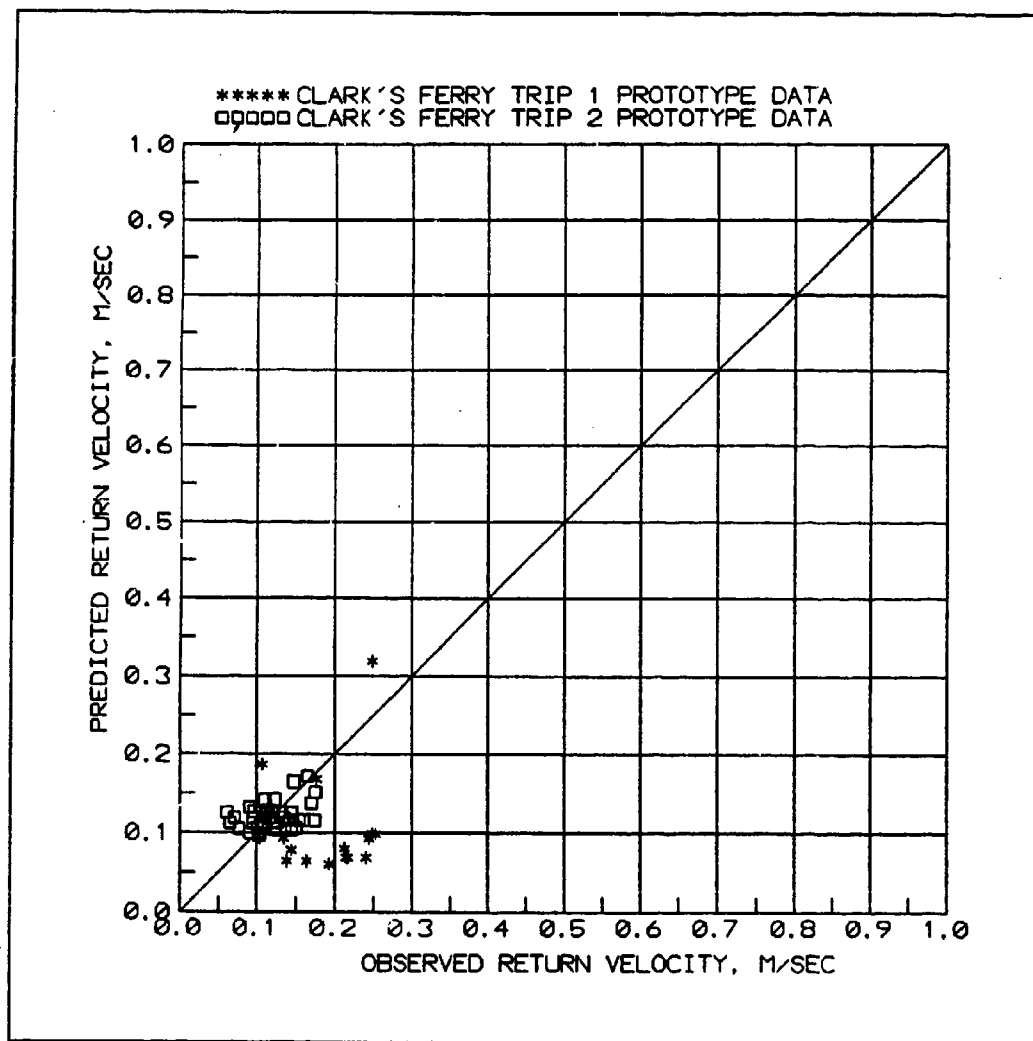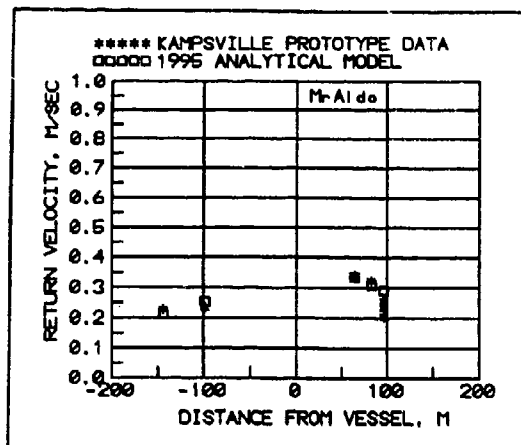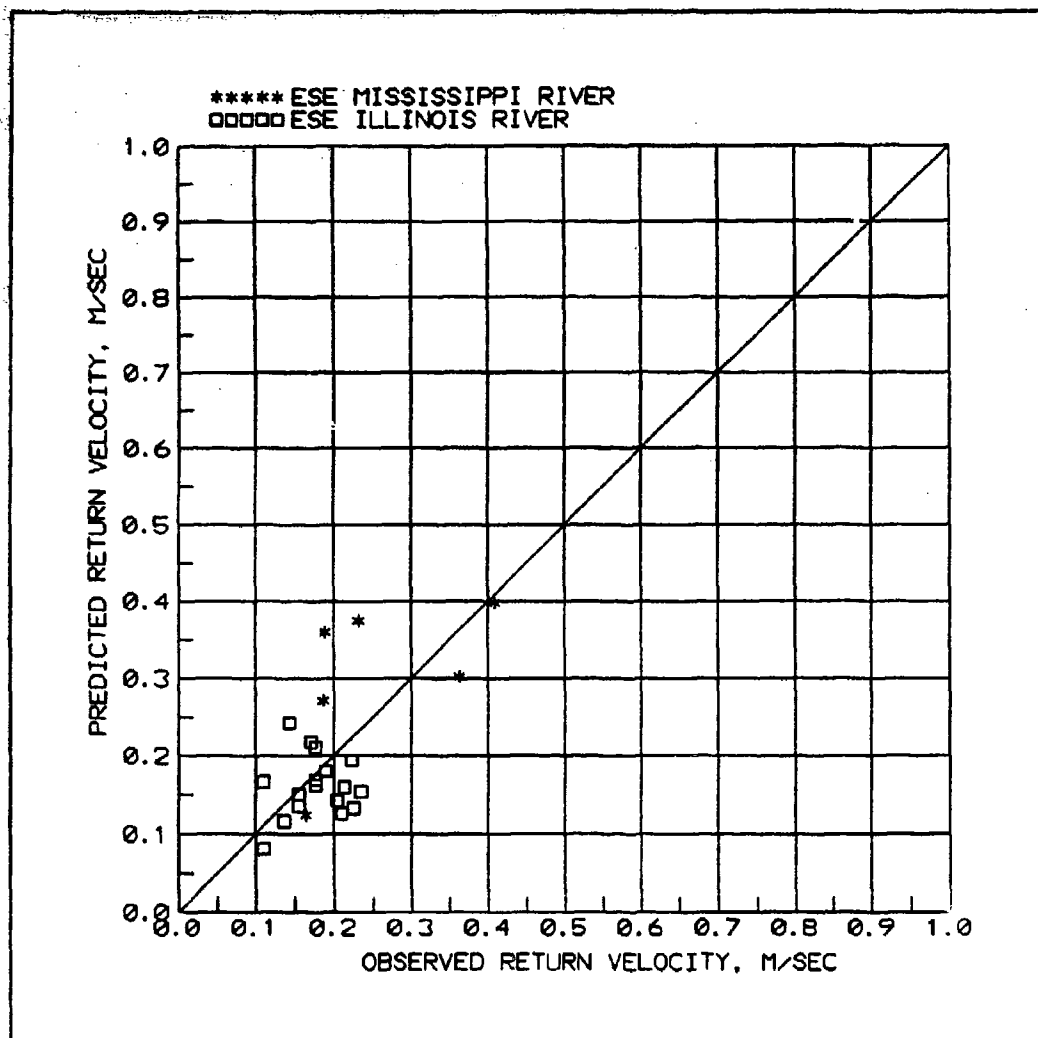
Figure 25. Observed ESE prototype return velocity versus computed return velocity using 1995 analytical method
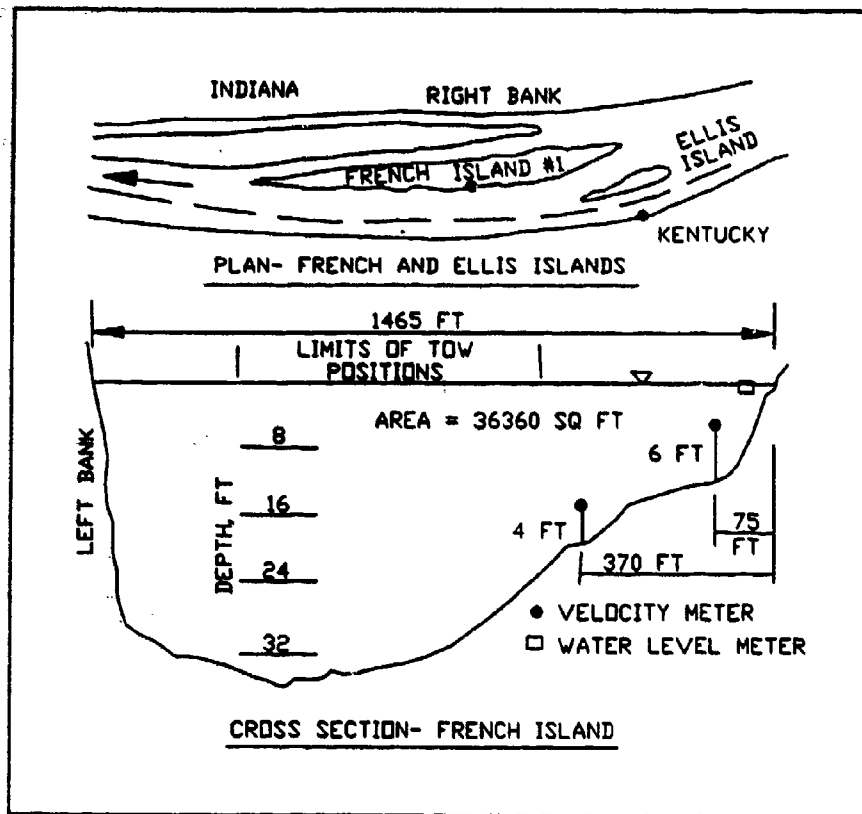
Figure 26. Cross section for ORL tests 89192-89196, French Island (Factor for converting feet to metric is 3.048 and square feet to square meters is 0.0929)

INDIANA   RIGHT BANK

ELLIS
ISLAND

FRENCH ISLAND #1

KENTUCKY

PLAN- FRENCH AND ELLIS ISLANDS

1020 FT

LIMITS OF TOW
POSITIONS

AREA = 20460 SQ FT

8 FT   8

DEPTH, FT   16

76
FT

24

CROSS SECTION- ELLIS ISLAND
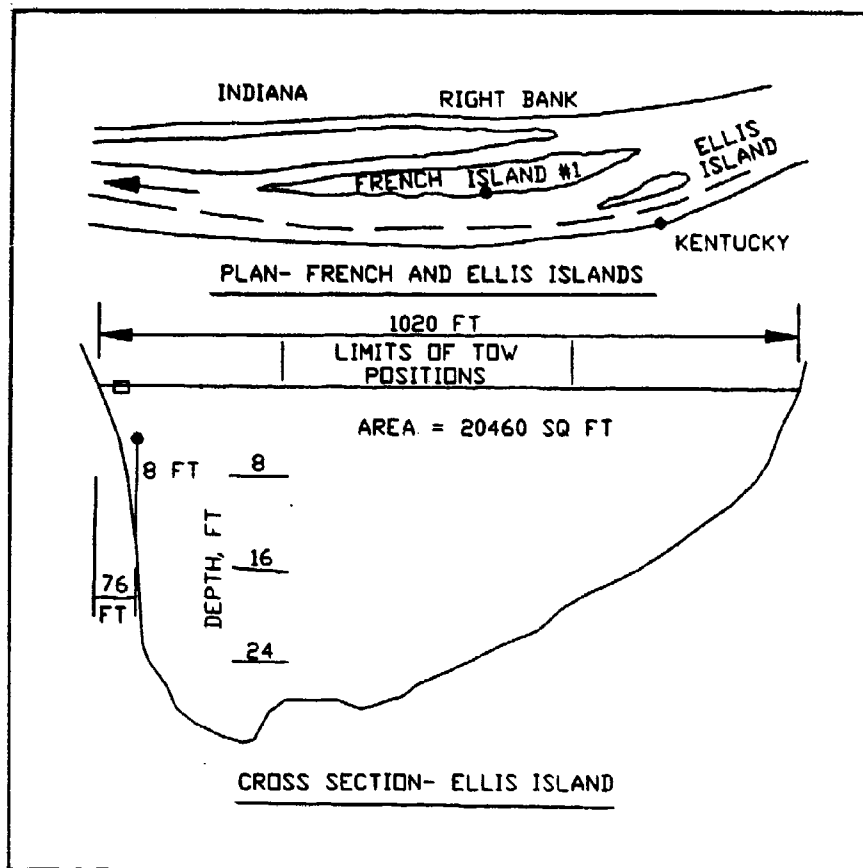
Figure 27. Cross section for ORL tests 89198-89203 — Ellis Island (Factor
for converting feet to meters is 3.048 and square feet to
square meters is 0.0929)
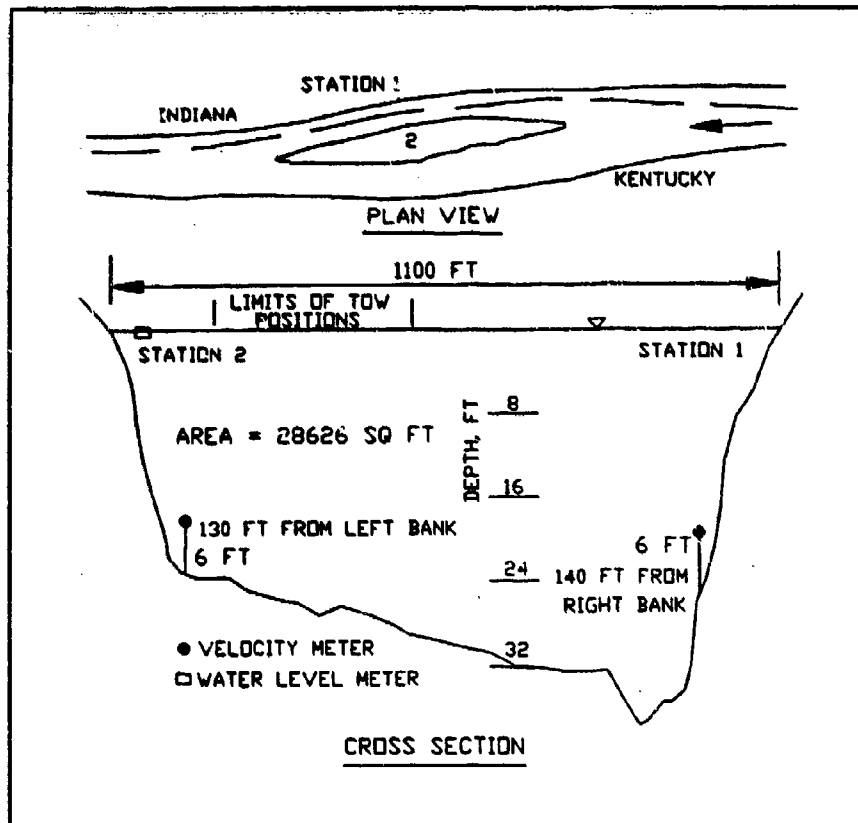
Figure 28. Cross section for ORL tests 90172-90179 (Factor for converting feet to meters is 3.048 and square feet to square meters is 0.0929)
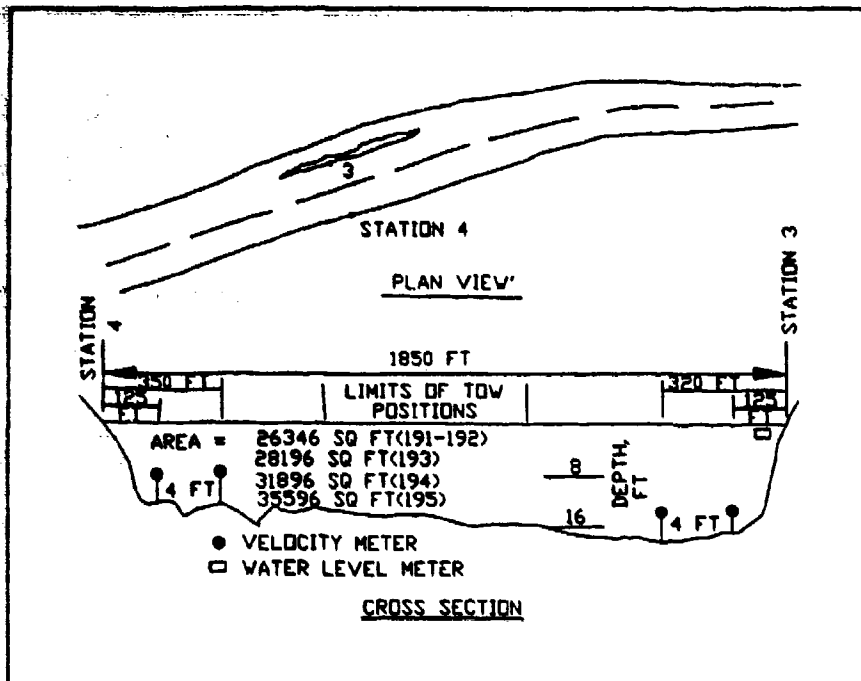
Figure 29. Cross section for ORL tests 90191-90195 (Factor for converting feet to meters is 3.048 and square feet to square meters is 0.0929)

Table 4
ORL Test 89192-89196

89192003	108	735	2	999	14.6	1.9	-1.0	19200	615	36360	1465
1390	0	0	10	6							
9999	9999	9999	9999	9999							
9999	9999	9999									
89192004	35	1040	9	999	7.02	1.9	1.0	10600	365	36360	1465
1390	0	0	10	6							
9999	9999	9999	9999	9999							
9999	9999	9999									
89192005	105	1125	9	999	13.5	1.9	-1.0	17600	565	36360	1465
1095	0.55	0	18	4							
1390	0.2	0	10	6							
9999	9999	9999									
89193001	105	1105	9	999	7.03	1.8	1.0	25700	815	36360	1465
1095	0.35	0	18	4							
1390	0.2	0	10	6							
1445	1	16									
89193003	54	688	9	999	10	1.8	1.0	10600	365	36360	1465
1390	0	0	10	6							
9999	9999	9999	9999	9999							
1445	0	16									
89193004	105	1140	2	999	11.1	1.8	1.0	14100	465	36360	1465
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
1445	1	16									
89193006	105	1163	9	999	6.8	1.8	1.0	10600	365	36360	1465
1390	0.35	0	10	6							
9999	9999	9999	9999	9999							
1445	0.7	16									
89194002	105	944	5.5	999	12.6	1.9	1.0	12300	415	36360	1465
1095	0.5	0	18	4							

9999 means data not recorded or meter malfunction.

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Chapter 6   Comparison of 1995 Analytical Method with Independent Field Data

Table 4 (Continued)

9999	9999	9999	9999	9999							
1445	1.5	16									
89194003	105	1120	9	999	11.9	1.9	-1.0	17600	565	36360	1465
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
1445	0.75	16									
89194005	70	365	2	999	5.86	1.9	1.0	14100	465	36360	1465
1390	0	0	10	6							
9999	9999	9999	9999	9999							
1445	0	16									
89195001	105	687	9	999	7.73	1.3	1.0	15400	515	36360	1465
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
1445	0	16									
89195002	105	1170	2	999	10.1	1.3	1.0	8900	315	36360	1465
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
1445	0.5	16									
89195003	108	1181	9	999	12.8	1.3	1.0	14100	465	36360	1465
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
1445	3	16									
89195004	105	731	9	999	8.54	1.3	1.0	15400	515	36360	1465
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
1445	0.7	16									
89195005	105	505	2	999	9.35	1.3	1.0	10600	365	36360	1465
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
1445	0.7	16									
89195006	175	1115	10	999	8.48	1.3	1.0	15400	530	36360	1465
1095	0.7	0	18	4							

(Sheet 2 of 3)

Table 4 (Concluded)											
1390	0.65	0	10	6							
1445	2.6	16									
89195008	105	1170	9	999	8.8	1.3	1.0	14100	465	36360	1465
1095	0.5	0	18	4							
1390	0.4	0	10	6							
1445	0.75	16									
89196001	175	1120	2	999	10.5	1.8	-1.0	29700	965	36360	1465
1095	0.8	0	18	4							
1390	0.55	0	10	6							
1445	2	16									
89196002	108	1082	2	999	16.7	1.8	-1.0	19200	615	36360	1465
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
1445	0	16									
89196003	54	720	9	999	13.5	1.8	1.0	25800	615	36360	1465
1095	0.4	0	18	4							
1390	0.3	0	10	6							
1445	2	16									
89196006	105	1115	9	999	12.5	1.8	-1.0	15000	490	36360	1465
1390	0.5	0	10	6							
9999	9999	9999	9999	9999							
1445	1.5	16									
89196007	54	1129	9	999	13.9	1.8	1.0	15400	515	36360	1465
1095	0.45	0	18	4							
1390	0.55	0	10	6							
1445	2.25	16									

Note: To convert to metric, multiply by these factors:
feet x 0.3048 to obtain meters
feet^2 x 0.0929 to obtain square meters
horsepower x 9809.5 to obtain watts
inches x 0.0254 to obtain meters

(Sheet 3 of 3)

Table 5
ORL Test 89198-89203

89198002	54	1000	0	999	11	1.1	1.0	12200	495	20460	1020
76	0.25	0	13	8							
20	1.5	4									
89198003	105	1139	9	999	12.5	1.1	-1.0	13500	545	20460	1020
76	0.65	0	13	8							
20	4.5	4									
89198004	175	1113	2	999	11.4	1.1	-1.0	12900	520	20460	1020
76	0.3	0	13	8							
20	2	4									
89198005	194	1115	9	999	7.25	1.1	-1.0	12900	520	20460	1020
76	0.5	0	13	8							
20	1.5	4									
89199001	105	1125	9	999	12.9	0.9	-1.0	13600	365	20460	1020
76	0.6	0	13	8							
20	5	4									
89199002	35	269	2	999	15.5	0.9	-1.0	11300	470	20460	1020
9999	9999	9999	9999	9999							
20	0	4									
89199003	245	1120	9	999	7.52	0.9	1.0	10300	430	20460	1020
76	1.05	0	13	8							
20	4	4									
89199004	105	1065	8	999	9.05	0.9	-1.0	11700	480	20460	1020
76	0.4	0	13	8							
20	1.5	4									
89200002	70	702	9	999	9.5	1	-1.0	15800	650	20460	1020
76	0.2	0	13	8							
20	1.5	4									
89200003	105	1155	9	999	12.2	1	1.0	14100	570	20460	1020
76	0.55	0	13	8							
20	2.25	4									
89201001	105	1139	2	999	11	1.8	1.8	14500	595	20460	1020

9999 means data not recorded or meter malfunction.

(Sheet 1 of 3)

Chapter 6   Comparison of 1995 Analytical Method with Independent Field Data

Table 5 (Continued)

9999	9999	9999	9999	9999							
20	1.5	4									
89201002	105	1170	9	999	13.6	1.8	-1.0	14100	570	20460	1020
76	0.45	0	13	8							
20	5	4									
89201003	105	1065	9	999	9.9	1.8	-1.0	6000	270	20460	1020
76	0.65	0	13	8							
20	1.5	4									
89201004	52	898	9	999	9.03	1.8	1.0	11300	470	20460	1020
76	0.3	0	13	9							
20	0.75	4	.								
89201005	105	882	2	999	13.1	1.8	-1.0	9800	410	20460	1020
76	0	0	13	8							
20	1	4									
89202001	105	702	9	999	10.6	1.8	-1.0	10700	445	20460	1020
9999	9999	9999	9999	9999							
20	1.5	4									
89202003	210	1167	9	999	10.4	1.8	-1.0	14200	575	20460	1020
9999	9999	9999	9999	9999							
20	7	4									
89202004	175	1129	2	999	7.94	1.8	-1.0	15600	640	20460	1020
9999	9999	9999	9999	9999							
20	1	4									
89202005	105	1115	9	999	11.5	1.8	-1.0	14600	595	20460	1020
9999	9999	9999	9999	9999							
20	3	4									
89202006	104	395	2	999	15.2	1.8	-1.0	12900	520	20460	1020
9999	9999	9999	9999	9999							
20	0.5	4									
89202007	41	96	5	999	12.5	1.8	-1.0	16600	690	20460	1020
9999	9999	9999	9999	9999							
20	0	4									

(Sheet 2 of 3)

Table 5 (Concluded)											
89202008	105	892	9	999	5.21	1.8	1.0	12900	520	20460	1020
9999	9999	9999	9999	9999							
20	1	4									
89203001	34	148	9	999	12.8	1.8	1.0	13100	530	20460	1020
9999	9999	9999	9999	9999							
2C	0	4									
89203002	105	1142	9	999	10.2	1.8	-1.0	11700	480	20460	1020
9999	9999	9999	9999	9999							
20	2	4									
89203003	70	892	9	999	9.1	1.8	1.0	13400	540	20460	1020
9999	9999	9999	9999	9999							
20	1.5	4									
89203004	105	1070	9	999	7.04	1.8	1.0	12700	480	20460	1020
9999	9999	9999	9999	9999							
20	1.5	4									
89203005	105	1113	9	999	9.8	1.8	-1.0	10200	420	20460	1020
9999	9999	9999	9999	9999							
20	1	4									

Note: To convert to metric, multiply by these factors:
feet x 0.3048 to obtain meters
feet^2 x 0.0929 to obtain square meters
horsepower x 9809.5 to obtain watts
inches x 0.0254 to obtain meters

(Sheet 3 of 3)

Table 6
ORL Test 90172-90179

90172004	105	687	9	999	7.61	0.9	1.0	7500	350	28626	1100
130	0.25	0	23	6							
960	0.15	0	25	6							
9999	9999	9999									
90172006	105	705	9	999	9.13	0.9	1.0	4200	225	28626	1100
960	0.25	0	25	6							
9999	9999	9999	9999	9999							
9999	9999	9999									
90172009	108	870	9	999	12.3	0.9	1.0	1000	100	28626	1100
130	0.75	0	23	6							
960	0.4	0	25	6							
20	5	4									
90173002	105	1113	2	999	8.55	0.7	1.0	7500	350	28626	1100
130	0.15	0	23	6							
960	0.1	0	25	6							
20	0.5	4									
90174003	105	1113	9	999	11.7	0.9	1.0	7500	350	28626	1100
130	0.7	0	23	6							
960	0.4	0	25	6							
20	4.5	4									
90174004	105	1139	9	999	12.1	0.9	-1.0	6700	325	28626	1100
130	0.4	0	23	6							
960	0.35	0	25	6							
20	3.5	4									
90174005	105	1080	9	999	9.97	0.9	-1.0	8900	400	28626	1100
130	0.4	0	23	6							
960	0.4	0	25	6							
20	2	4									
90175002	105	1115	9	999	7.9	1	1.0	8900	400	28626	1100
130	0.25	0	23	6							

9999 means data not recorded or meter malfunction.

(Continued)

Chapter 6   Comparison of 1995 Analytical Method with Independent Field Data

Table 6 (Concluded)

960	0.2	0	23	6							
20	2	4									
90176001	105	1125	9	999	9.92	0.7	1.0	7500	350	28626	1100
130	0.4	0	23	6							
960	0.3	0	25	6							
20	1.5	4									
90176002	105	1105	9	999	11.2	0.7	-1.0	8800	400	28626	1100
130	0.4	0	23	6							
960	0.3	0	25	6							
20	1.5	4									
90176003	35	687	9	999	10.8	0.7	1.0	4800	250	28626	1100
130	0.15	0	23	6							
960	0	0	25	6							
20	2	4									
90177002	105	1115	9	999	11.5	0.7	-1.0	11600	500	28626	1100
130	0.35	0	23	6							
960	0.25	0	25	6							
20	2.5	4									
90179005	108	1085	9	999	12.1	0.6	-1.0	6800	330	28626	1100
960	0.3	0	25	6							
130	0.4	0	23	6							
20	3	4									
90179006	70	738	9	999	18.5	0.6	1.0	7500	350	28626	1100
130	0.4	0	23	6							
960	0.15	0	25	6							
20	3	4									

Note: To convert to metric, multiply by these factors:
feet x 0.3048 to obtain meters
feet^2 x 0.0929 to obtain square meters
horsepower x 9809.5 to obtain watts
inches x 0.0254 to obtain meters

Table 7
ORL Test 90191-90195

90191002	105	1170	2	999	9.24	0.6	1.0	13500	1050	26346	1850
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
1530	0.2	0	18	4							
1725	0.1	0	17	4							
9999	9999	9999									
90191003	35	328	2	999	13.7	0.6	-1.0	13500	1050	26346	1850
350	0.05	0	13	4							
125	0.15	0	12	4							
1530	0.2	0	18	4							
1725	0	0	17	4							
9999	9999	9999									
90191005	108	739	2	999	22.5	0.6	-1.0	15200	1150	26346	1850
350	0.15	0	13	4							
125	0.1	0	12	4							
1530	0.35	0	18	4							
1725	0.15	0	17	4							
9999	9999	9999									
90191006	50	1185	9	999	9.72	0.6	1.0	10600	850	26346	1850
350	0.15	0	13	4							
125	0.1	0	12	4							
1530	0.15	0	18	4							
1725	0.1	0	17	4							
9999	9999	9999									
90192001	105	1143	9	999	9.51	1.1	-1.0	12400	975	26346	1850
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
1530	0	0	18	4							
1725	0	0	17	4							
1830	0	10									

9999 means data not recorded or meter malfunction.

(Sheet 1 of 4)

Table 7 (Continued)											
90192003	105	1139	2	999	8.9	1.1	1.0	14400	1100	26346	1850
350	0.2	0	13	4							
125	0.3	0	12	4							
1530	0.45	0	18	4							
1725	0.3	0	17	4							
1830	2.5	10									
90192004	105	750	9	999	13.2	1.1	-1.0	14400	1100	26346	1850
350	0.1	0	13	4							
125	0.25	0	12	4							
1530	0.75	0	18	4							
1725	0.4	0	17	4							
1830	3.25	10									
90193001	50	914	9	999	10.4	1.1	1.0	13375	975	28196	1850
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
350	0.15	0	13	4							
1830	1.5	10									
90193002	106	700	2	999	13.1	1.1	-1.0	13800	1000	28196	1850
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
350	0	0	13	4							
125	0	0	12	4							
1830	0.75	10									
90193003	105	1135	9	999	7.03	1.1	1.0	13800	1000	28196	1850
9999	9999	9999	9999	9999							
350	0.15	0	13	4							
125	0.2	0	12	4							
1530	0.4	0	18	4							
1830	1.5	10									
90193004	108	439	2	999	17.2	1.1	-1.0	14650	1050	28196	1850
9999	9999	9999	9999	9999							

(Sheet 2 of 4)

Chapter 6   Comparison of 1995 Analytical Method with Independent Field Data

Table 7 (Continued)

9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
1830	0.5	0									
90193005	108	710	2	999	14.8	1.1	-1.0	15825	1125	28196	1850
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
350	0	0	13	4							
125	0	0	12	4							
1830	1	10									
90194001	105	918	9	999	10.4	1.6	1.0	15800	1000	31896	1850
9999	9999	9999	9999	9999							
350	0.9	0	13	4							
125	0.35	0	12	4							
1530	0.5	0	18	4							
1830	3	10									
90194004	50	720	9	999	9.09	1.6	1.0	12400	800	31896	1850
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
1830	0	10									
90195001	105	1143	9	999	8.95	2.6	1.0	14850	850	35596	1850
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
1530	0.5	0	18	4							
1830	1.5	10									
90195002	105	1141	9	999	8.51	2.6	1.0	19900	1100	35596	1850
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							

(Sheet 3 of 4)

Table 7 (Concluded)

125	0.45	0	12	4							
1530	0.55	0	18	4							
1830	2	10									
90195003	140	1143	2	999	16.5	2.6	-1.0	22950	1250	35596	1850
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
1830	2	10									
90195004	105	1175	2	999	9.19	2.6	1.0	12100	700	35596	1850
9999	9999	9999	9999	9999							
9999	9999	9999	9999	9999							
125	0	0	12	4							
1530	0	0	18	4							
1830	0	10									

Note: To convert to metric, multiply by these factors:
feet x 0.3048 to obtain meters
feet^2 x 0.0929 to obtain square meters
horsepower x 9809.5 to obtain watts
inches x 0.0254 to obtain meters

Description of items in database:
First line:
1. Test name
2. Vessel beam, feet
3. Length of barges, feet
4. Draft of barges, feet
5. Towboat power, horsepower
6. Vessel speed relative to ground, feet/second
7. Ambient velocity = Discharge/total channel area, feet/second
8. Upbound = 1.0, Downbound = -1.0
9. Channel area left of tow center line, feet^2
10. Distance from left bank to tow center line, feet
11. Total channel area, feet^2
12. Total water surface width, feet
Next 1,2, or 4 lines:
1. Distance from left bank to velocity meter, feet
2. Maximum (upbound) or minimum (downbound) velocity alongside tow, feet/second
3. Ambient velocity at this meter, feet/second
4. Local depth at meter, feet
5. Distance from meter to bottom, feet
Next 1 line:
1. Distance from left bank to wave gauge, feet
2. Water-level drawdown, inches
3. Local depth at wave gauge, feet

(Sheet 4 of 4)
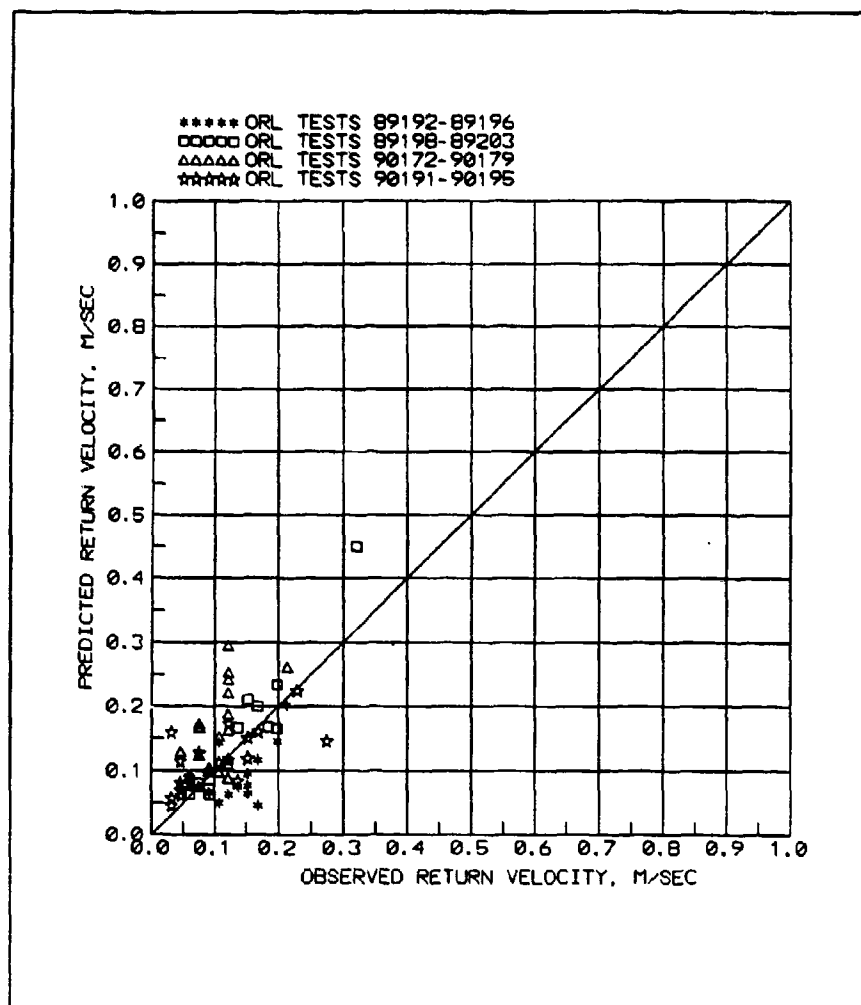
Figure 30. Observed ORL prototype return velocity versus computed return
velocity using 1995 analytical method
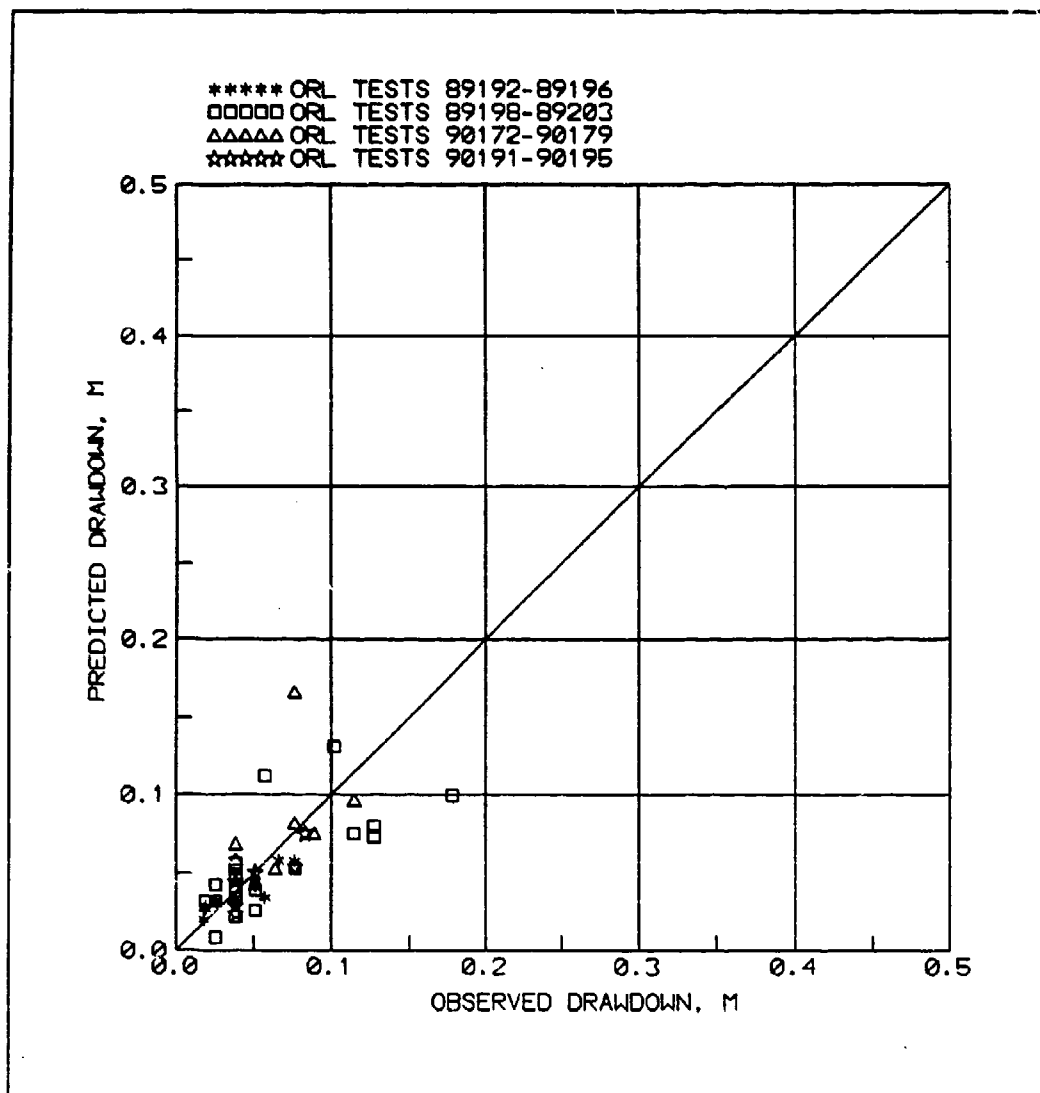
Figure 31. Observed ORL prototype drawdown versus computed drawdown using 1995 analytical method

7 Program NAVEFF

The 1995 analytical method for return velocity and drawdown was programmed in QuickBASIC 4.5 language as shown in the program listing in Figure 32. The program prompts for metric or english units and then requests the following:

a. Total channel top width in meters or feet.

b. Distance from tow center line to left bank in meters or feet (when facing downsteam).

c. Total channel cross-sectional area in square meters or square feet.

d. Channel cross-sectional area from tow center line to left bank.

e. Tow draft in meters or feet.

f. Total barge width in meters or feet.

g. Total barge length in meters or feet. In determining the displacement thickness used to determine effective draft and beam, a single temperature of 17 °C is used because of lack of sensitivity to temperature.

h. Average channel velocity in meters/sec or ft/sec. The program applies a factor of 1.2 to the average channel velocity to determine the vessel speed relative to the water.

i. Vessel speed relative to ground in meters/second or feet/second.

j. Direction of travel U or u for upbound, D or d for downbound.

The program then outputs $V_r(Y)$ in m/sec or ft/sec and z(Y) in meters or feet at five points on each side of the tow. The five points are equally spaced and begin at one tow width away from the vessel center line and end at the shoreline. The program then prompts for a new vessel speed using the same channel and tow geometry. The program will indicate if the speed entered

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```
'PROGRAM NAVEFF.BAS-BASED ON SCHIJF FOR ENTIRE CHANNEL
'AND 1995 WES REPT ON RETURN VELOCITY AND DRAWDOWN
REM THIS PRINTS OUT ALL DATA AND GIVES A VISUAL PICTURE
CLS
SCREEN 9
COLOR 11, 4
LINE (700, 600)-(0, 0), 4, BF
PRINT
PRINT TAB(12); "PROGRAM NAVEFF.BAS-SCHIJF METHOD PLUS EMPIRICISM"
PC = 0
PRINT
PRINT " EXPERIMENTAL DATA USED IN DEVELOPMENT LIMITED TO THE FOLLOWING:"
PRINT " BLOCKAGE RATIO LESS THAN 85"
PRINT " DISTANCE ON SIDE OF VESSEL GREATER THAN 10% OF TOTAL CHANNEL WIDTH"
PRINT "      AND GREATER THAN VESSEL BEAM"
PRINT " VESSEL LENGTH GREATER THAN 40% OF CHANNEL WIDTH"
PRINT " RETURN VELOCITY AND DRAWDOWN LIMITED TO ONE BEAM WIDTH AWAY"
PRINT "      FROM VESSEL CENTERLINE OUT TO THE SHORELINE"
PRINT " VESSEL SPEED RELATIVE TO WATER SHOULD BE 0.35-0.9*LIMIT SPEED"
FOR I = 1 TO 10
PRINT
NEXT I
PRINT TAB(25); "Press SPACE BAR to Continue"
SLEEP
CLS
'
FLAG1$ = "N"
FLAG2$ = "N"
5 INPUT "ENGLISH OR METRIC UNITS (E OR M)  ", uni$
  IF uni$ = "E" OR uni$ = "e" THEN FLAG1$ = "Y"
  IF uni$ = "M" OR uni$ = "m" THEN FLAG2$ = "Y"
  IF FLAG1$ = "Y" OR FLAG2$ = "Y" THEN GOTO 7
  GOTO 5
7 '
  INPUT "ENTER TOTAL CHANNEL TOP WIDTH ", BTOTAL
8 INPUT "ENTER DISTANCE FROM TOW CENTERLINE TO LEFT BANK ", BLEFT
  INPUT "ENTER TOTAL CHANNEL AREA ", ATOTAL
  INPUT "ENTER AREA LEFT OF TOW CENTERLINE ", ALEFT
  INPUT "ENTER BARGE DRAFT ", D
  INPUT "ENTER TOTAL BARGE WIDTH ", B
  IF B < BLEFT AND B < BTOTAL - BLEFT THEN GOTO 9
  PRINT "DISTANCE FROM VESSEL CENTERLINE TO BANK MUST BE > VESSEL BEAM"
  GOTO 8
9 INPUT "ENTER TOTAL LENGTH OF BARGES ", L
  INPUT "ENTER AVERAGE CHANNEL VELOCITY, + FOR UPBOUND, - FOR DOWN ", VAM
10 INPUT "ENTER TOW SPEED RELATIVE TO GROUND ", VG
  V = VG + 1.2 * VAM
  GRAV = 32.16
  FLAG$ = "N"
  IF uni$ = "M" THEN GRAV = 9.805
  IF uni$ = "m" THEN GRAV = 9.805
  LUNIT$ = "FEET   "
  VUNIT$ = "FEET/SEC"
  AUNIT$ = "SQ FT"
  IF uni$ = "M" OR uni$ = "m" THEN LUNIT$ = "METERS"
  IF uni$ = "M" OR uni$ = "m" THEN VUNIT$ = "M/SEC   "
  IF uni$ = "M" OR uni$ = "m" THEN AUNIT$ = "SQ M "
  '
  ' SET WATER VISCOSITY = 0.0000011 M**2/SEC FOR TEMP = 17 DEG C
```

Figure 32. Listing for PC program NAVEFF (Sheet 1 of 12)

```
     VNU = .0000011
     IF LUNIT$ = "FEET" THEN VNU = VNU * 3.28 * 3.28
     '
     ' COMPUTE GEOMETRIC FACTORS
     '
     AM = B * D
     BRIGHT = BTOTAL - BLEFT
     ARIGHT = ATOTAL - ALEFT
     NSIDEL = 2 * ALEFT / AM
     NSIDER = 2 * ARIGHT / AM
     SKEWL = ATOTAL / 2 / ALEFT
     BLB = BLEFT / BTOTAL
     IF BLB > .9 OR BLB < .1 THEN FLAG$ = "Y"
     SKEWR = ATOTAL / 2 / ARIGHT
     BRB = BRIGHT / BTOTAL
     IF BRB > .9 OR BRB < .1 THEN FLAG$ = "Y"
     IF FLAG$ = "N" THEN GOTO 20
     CLS
     PRINT
     PRINT "  WARNING, THE DATA ENTERED FOR THE WIDTH ON ONE SIDE OF THE TOW ";
     PRINT "  IS LESS THAN 10% OF THE TOTAL CHANNEL WIDTH. THIS IS OUTSIDE THE";
     PRINT "  LIMITS OF THE EXPERIMENTAL DATA."
     FOR I = 1 TO 15
     PRINT
     NEXT I
     PRINT TAB(25); "Press SPACE BAR to Continue"
     SLEEP
     CLS
     IF L >= .4 * BTOTAL THEN GOTO 14
     CLS
     PRINT
     PRINT "   WARNING, THE DATA ENTERED FOR THE VESSEL LENGTH ";
     PRINT "   IS LESS THAN 40% OF THE TOTAL CHANNEL WIDTH.  THIS IS OUTSIDE THE"
     PRINT "   LIMITS OF THE EXPERIMENTAL DATA."
     FOR I = 1 TO 15
     PRINT
     NEXT I
     PRINT TAB(25); "Press SPACE BAR to Continue"
     SLEEP
     CLS
14   '
20   H = ATOTAL / BTOTAL
     N = ATOTAL / AM
     En = N
     IF N < 85 THEN GOTO 30
     CLS
     PRINT
     PRINT "   WARNING, THE BLOCKAGE RATIO IS GREATER THAN 85, WHICH IS OUTSIDE "
     PRINT "   THE LIMITS OF THE EXPERIMENTAL DATA."
     FOR I = 1 TO 15
     PRINT
     NEXT I
     PRINT TAB(25); "Press SPACE BAR to Continue"
     SLEEP
     CLS
30   '
     REM 'SOLVE SCHIJF EQUATION FOR DISPLACEMENT CALCULATION
     '
     Z = .01
```

Figure 32. (Sheet 2 of 12)

```
40  SCHIJF = (1 + N * Z / H) / (N - 1 - N * Z / H)
    ZT = (V ^ 2 / 2 / GRAV) * ((SCHIJF ^ 2) + 2 * SCHIJF)
    U1 = V * SCHIJF
    IF ABS((ZT - Z) / ZT) < .00001 THEN GOTO 50
    IF Z > 20 THEN GOTO 100
    Z = ZT
    GOTO 40
50  REM
    REM COMPUTE DISPLACEMENT THICKNESS
    REM
    VDISP = V + U1
    RL = VDISP * L / VNU
    DISP = .292 * L / (.43429 * LOG(RL)) ^ 2.58
    DE = D + DISP
    BE = B + 2 * DISP
    N = ATOTAL / BE / DE
    REM 'SOLVE SCHIJF EQUATION FOR RETURN VELOCITY
    '
    Z = .01
51  SCHIJF = (1 + N * Z / H) / (N - 1 - N * Z / H)
    ZT = (V ^ 2 / 2 / GRAV) * ((SCHIJF ^ 2) + 2 * SCHIJF)
    U1 = V * SCHIJF
    IF ABS((ZT - Z) / ZT) < .00001 THEN GOTO 52
    IF Z > 20 THEN GOTO 100
    Z = ZT
    GOTO 51
52  REM
    REM 'SOLVE SCHIJF EQUATION FOR LIMIT SPEED USING NEWTON RAPHSON
    '
    VLO = V
54  RTEM = VLO ^ 2 / GRAV / H
    FV = 1 - 1 / N + .5 * RTEM - 1.5 * RTEM ^ (1 / 3)
    FPV = VLO / GRAV / H - (VLO ^ (-1 / 3)) / (GRAV * H) ^ (1 / 3)
    VLN = VLO - FV / FPV
    IF ABS((VLO - VLN) / VLO) < .0001 THEN GOTO 55
    VLO = VLN
    GOTO 54
55  VL = VLN
58  VLIMRAT = V / VL
    PRINT
    IF VLIMRAT > .35 THEN GOTO 59
    PRINT "WARNING******** SPEED LESS THAN 0.35*LIMIT SPEED ******** "
59  IF VLIMRAT < .9 THEN GOTO 61
    PRINT "WARNING******** SPEED GREATER THAN 0.9*LIMIT SPEED ********"
61  '
    ' APPLY CORRECTION FACTOR
    '
    CF = 1.78 - 1.07 * VLIMRAT
    IF CF < 1 THEN CF = 1!
    U1 = CF * U1
    ZT = (V + U1) ^ 2 / 2 / GRAV - V ^ 2 / 2 / GRAV
    PRINT
    '
    REM COMPUTE a(ALF) AND AVERAGE Vr FOR EACH
    REM SIDE OF TOW
    '
    VFACTL = 1.65 - 1.3 * BLB
    IF BLB > .5 THEN VFACTL = 1.35 - .7 * BLB
    VFACTR = 1.65 - 1.3 * BRB
    IF BRB > .5 THEN VFACTR = 1.35 - .7 * BRB
```

Figure 32. (Sheet 3 of 12)

```
VRAL = U1 * VFACTL
VRAR = U1 * VFACTR
ZSL = ZT * VFACTL
ZSR = ZT * VFACTR
ALFL = .75 * NSIDEL ^ .18
ALFR = .75 * NSIDER ^ .18
IF ALFL < 1 THEN ALFL = 1
IF ALFR < 1 THEN ALFR = 1
ZALFL = ALFL ^ .5
ZALFR = ALFR ^ .5
'
'
VRLM = ALFL * VRAL
VRRM = ALFR * VRAR
ZSML = ZALFL * ZSL
ZSMR = ZALFR * ZSR
'
'
PRINT TAB(22); "DATA SHOWN IS THE INPUT DATA"
PRINT
PRINT " CHANNEL TOTAL AREA "; USING "######.#"; ATOTAL;
PRINT " "; AUNIT$;
PRINT "    AREA LEFT OF TOW           "; USING "######.#"; ALEFT;
PRINT " "; AUNIT$
PRINT "          TOTAL WIDTH "; USING "#####.#"; BTOTAL;
PRINT " "; LUNIT$;
PRINT "  DISTANCE, LEFT BANK TO TOW "; USING "#####.#"; BLEFT;
PRINT " "; LUNIT$
PRINT " TOW      WIDTH      "; USING "#####.#"; B;
PRINT " "; LUNIT$; " DRAFT               "; USING "####.##"; D;
PRINT " "; LUNIT$
PRINT " TOW      LENGTH     "; USING "#####.#"; L;
PRINT " "; LUNIT$
PRINT " TOW SPEED RELATIVE TO GROUND     "; USING "####.##"; VG;
PRINT " "; VUNIT$
PRINT " AVERAGE CHANNEL VELOCITY(+=UPBOUND,-=DOWN) "; USING "####.##"; VAM;
PRINT " "; VUNIT$
PRINT
'
FOR I = 1 TO 10
PRINT
NEXT I
PRINT TAB(25); "Press SPACE BAR to Continue"
SLEEP
CLS
IF ARIGHT > ALEFT AND VRRM > VRLM THEN VRRM = VRLM
IF ALEFT > ARIGHT AND VRLM > VRRM THEN VRLM = VRRM
'
'COMPUTE RETURN VELOCITY AND DRAWDOWN DISTRIBUTION
'
PRINT
PRINT TAB(15); "COMPUTED RETURN VELOCITY AND DRAWDOWN DISTRIBUTION"
PRINT
PRINT TAB(15); "DISTANCE"; TAB(37); "RETURN"; TAB(54); "DRAWDOWN"
PRINT TAB(15); "FROM TOW CL"; TAB(37); "VELOCITY"
PRINT TAB(15); LUNIT$; TAB(37); VUNIT$; TAB(54); LUNIT$
PRINT
FOR J = 1 TO 2
IF J = 2 THEN GOTO 60
ALF = ALFL: VRM = VRLM
```

Figure 32. (Sheet 4 of 12)

```
      ZALF = ZALFL: ZSM = ZSML
      BSIDE = BLEFT
      GOTO 70
 60   ALF = ALFR: VRM = VRRM
      ZALF = ZALFR: ZSM = ZSMR
      BSIDE = BRIGHT
 70   C = 3! * LOG(1 / ALF)
      ZC = 3! * LOG(1 / ZALF)
      '
      '
      YLAST = 0
      FOR I = 1 TO 5
      IF J = 1 THEN dum = -BSIDE
      IF J = 2 THEN dum = B
      Y = (dum + (I - 1) / 4 * (BSIDE - B))
      yy = ABS(Y)
      VY = VRM * EXP(C * (yy - B) / (BSIDE - B))
      ZY = ZSM * EXP(ZC * (yy - B) / (BSIDE - B))
      LOCA$ = " "
      IF J = 1 AND I = 1 THEN LOCA$ = "  LEFT BANK"
      IF J = 2 AND I = 5 THEN LOCA$ = "  RIGHT BANK"
      IF (I = 1) AND (J = 1) THEN VYQL = VY: ZLQ = ZY
      IF (I = 1) AND (J = 2) THEN VYQR = VY: ZRQ = ZY
      PRINT LOCA$;
      PRINT TAB(15); USING "#####.#"; Y;
      PRINT TAB(30); USING "#########.###"; VY;
      PRINT TAB(45); USING "##########.###"; ZY
      YLAST = Y
      NEXT I
      NEXT J
      FOR I = 1 TO 5
      PRINT
      NEXT I
      PRINT TAB(25); "Press SPACE BAR to Continue"
      SLEEP
      GOTO 130
100   PRINT "SPEED EQUAL TO OR GREATER THAN VLIMIT"
      GOTO 10
130   CLS
      PRINT
      INPUT "        ENTER 1 FOR A PRINTOUT OF THE INPUT DATA AND RESULTS"; PRN1
      IF PRN1 = 1 THEN GOSUB PAPER
       PRINT
      INPUT "        ENTER 1 FOR A VISUAL DISPLAY OF THE RESULTS"; ANS1
      IF ANS1 = 1 THEN GOSUB PICTURE
      CLS
160   PRINT
      INPUT "        ENTER 1 FOR A NEW VESSEL SPEED OR 2 TO QUIT"; ANS2
      IF ANS2 = 1 THEN CLS : GOTO 10 ELSE CLS : END

PICTURE:
      CLS
      SCREEN 9

REM ADJUSTMENT FACTOR
      RAT = 560 / BTOTAL
      DMAX = (.75) * ((ALEFT / BLEFT) + (ARIGHT / BRIGHT))
      DMRAT = DMAX * RAT
      SELECT CASE DMRAT
       CASE IS > 60
```

Figure 32. (Sheet 5 of 12)

```
                   m = 1
            CASE 40 TO 60
                   m = 2
            CASE 26 TO 39
                   m = 3
            CASE 20 TO 25
                   m = 4
            CASE 1 TO 19
                   m = 5
            END SELECT

        REM BARGE
          DM = D * m
          BLRAT = BLEFT * RAT
          BRRAT = BRIGHT * RAT
          DRAT = D * RAT * m
          DRTOT = 4.6
          IF AUNIT$ = "SQ FT" THEN DRTOT = 3.28 * DRTOT
          DT = (DRTOT - D)
          DTRAT = DT * RAT * m
          bRAT = B * RAT
          BLRATA = BLRAT + 40
          blbc = BLRATA - (bRAT) / 2
          brbc = BLRATA + (bRAT) / 2
          brtc = brbc
          bltc = blbc
          blbr = 160 + DRAT
          brbr = blbr
          brtr = 160 - DTRAT
          bltr = brtr
          LINE (bltc, bltr)-(brbc, brbr), , B
          LINE (40, 160)-(600, 160)

        REM FRAME WORK
          RAT = 560 / BTOTAL
          BLRAT = BLEFT * RAT
          BRRAT = BRIGHT * RAT
          IF VYQL > VYQR THEN VYQ = VYQL ELSE VYQ = VYQR
          IF ZLQ > ZRQ THEN ZQ = ZLQ ELSE ZQ = ZRQ
          IF VYQ < .2 THEN VRAT = 350:   VP = .2
          IF (VYQ > .2) AND (VYQ < .5) THEN VRAT = 140:   VP = .5
          IF (VYQ > .5) AND (VYQ < 1!) THEN VRAT = 70:   VP = 1!
          IF (VYQ > 1!) AND (VYQ < 2!) THEN VRAT = 35:  VP = 2!
          IF (VYQ > 2!) AND (VYQ < 5!) THEN VRAT = 14:  VP = 5!
          IF (VYQ > 5!) AND (VYQ < 10!) THEN VRAT = 7:  VP = 10!
          IF (ZQ < .1) THEN DRAT = 700: DP = .1
          IF (ZQ > .1) AND (ZQ < .2) THEN DRAT = 350: DP = .2
          IF (ZQ > .2) AND (ZQ < .5) THEN DRAT = 140: DP = .5
          IF (ZQ > .5) AND (ZQ < 1) THEN DRAT = 70: DP = 1!
          IF (ZQ > 1!) AND (ZQ < 2) THEN DRAT = 35: DP = 2!
          IF (ZQ > 2!) AND (ZQ < 5) THEN DRAT = 14: DP = 5!
        PRINT VP; "                    ";
        PRINT TAB(33); "RETURN VELOCITY"
          PRINT TAB(12); "LEFT"; TAB(60); "RIGHT"
        PRINT
        IF uni$ = "m" OR uni$ = "M" THEN
          PRINT "M/SEC"
          PRINT
          PRINT "   0   "; BLEFT; "  <   0"; TAB(60); "0   >  "; BRIGHT
          PRINT TAB(36); "DRAWDOWN"
```

Figure 32. (Sheet 6 of 12)

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```
            PRINT
            PRINT " M"
            ELSE
            PRINT "F/SEC"
            PRINT
            PRINT "  0    "; BLEFT; "  <   0"; TAB(60); "0   >  "; BRIGHT
            PRINT TAB(36); "DRAWDOWN"
            PRINT
            PRINT " FT"
            END IF
        PRINT
        PRINT DP
        LINE (40, 5)-(40, 160)
        LINE (40, 80)-(600, 80)
        LINE (600, 5)-(600, 160)
        LINE (40, 290)-(600, 290)
        LINE (35, 10)-(45, 10)
        LINE (35, 150)-(45, 150)
        FOR I = 1 TO 8
         PRINT
        NEXT I

        REM XSECTION
         DMAX = (.75) * ((ALEFT / BLEFT) + (ARIGHT / BRIGHT))
         DLEFT = ((2 * ARIGHT) / BRIGHT) - (DMAX / 2)
         DRIGHT = ((2 * ARIGHT) / BRIGHT) - (DMAX / 2)
         BRRAT = BRIGHT * RAT
         DLRAT = DLEFT * RAT
         DRRAT = DRIGHT * RAT
         DMRAT = DMAX * RAT
         SELECT CASE DMRAT
          CASE IS > 60
           m = 1
          CASE 40 TO 60
           m = 2
          CASE 26 TO 39
           m = 3
          CASE 20 TO 25
           m = 4
          CASE 1 TO 19
           m = 5
          END SELECT
        DLRAT = DLRAT * m
        DRRAT = DRRAT * m
        DMRAT = DMRAT * m
        BLP1C = BLRAT / 2 + 40
        BLP2C = BLEFT * RAT + 40
        BRP1C = BRRAT / 2 + 40 + BLP2C
        BLP1R = DLRAT + 160
        BLP2R = DMRAT + 160
        BRP1R = DRRAT + 160
        LINE (1, 152)-(30, 152)
        LINE (30, 152)-(40, 160)
        LINE (40, 160)-(BLP1C, BLP1R)
        LINE (BLP1C, BLP1R)-(BLP2C, BLP2R)
        LINE (BLP2C, BLP2R)-(BRP1C, BRP1R)
        LINE (BRP1C, BRP1R)-(600, 160)
        LINE (600, 160)-(610, 152)
        LINE (610, 152)-(640, 152)
        LINE (BLP2C, 150)-(BLP2C, 5)
```

Figure 32. (Sheet 7 of 12)

```
   DLRAT = DLEFT * RAT
   DRRAT = DRIGHT * RAT
   DMRAT = DMAX * RAT
   PRINT TAB(30); "BED CROSS-SECTION"
   PRINT
   PRINT "  Bed Depth & Barge Draft are Increased by a Factor of"; m;
   PRINT "for Display Purposes"
   PRINT TAB(10); "Barge Location and Size are to Scale(hit space bar to continue)

REM PROP
IF BTOTAL < 150 THEN
 DIM PX(15), PY(15)
 IF PC = 0 THEN
 FOR I = 1 TO 12
  READ PX(I)
  READ PY(I)
 NEXT I
 DATA 10,13,15,17,20,20,24,27,28,30,30,28,28,24,20,20,18,16,15,12,14,10,10,13
 PC = 1
 END IF
 FOR I = 1 TO 11
  LINE (PX(I) + BLRAT + 20, PY(I) + 140)-(PX(I + 1) + BLRAT + 20, PY(I + 1) + 14
 NEXT I
END IF

REM DRAWDOWN & VELOCITY LEFT SIDE
    ALF = ALFL: VRM = VRLM
    ZALF = ZALFL: ZSM = ZSML
    BSIDE = BLEFT
     C = 3! * LOG(1 / ALF)
     ZC = 3! * LOG(1 / ZALF)
     '
    'REM Y=DISTANCE     VY=VELOCITY      ZY=DRAWDOWN
     REM YL(I)-YLC(I)   VYL(I)-VYLR(I)   ZL(I)-ZLR(I)

     FOR I = 1 TO 5
     dum = -BSIDE
     Y = (dum + (I - 1) / 4 * (BSIDE - B))
     YL(I) = -Y
     YLC(I) = (BLRAT + 40) - (RAT * YL(I))
     yy = ABS(YL(I))
     VYL(I) = VRM * EXP(C * (yy - B) / (BSIDE - B))
     VYLR(I) = 80 - (VYL(I) * VRAT)
     ZL(I) = ZSM * EXP(ZC * (yy - B) / (BSIDE - B))
     ZLR(I) = ZL(I) * DRAT + 85
     NEXT I

REM DRAWDOWN & VELOCITY RIGHT SIDE
    ALF = ALFR: VRM = VRRM
    ZALF = ZALFR: ZSM = ZSMR
    BSIDE = BRIGHT
     C = 3! * LOG(1 / ALF)
     ZC = 3! * LOG(1 / ZALF)
     '
     REM Y=DISTANCE     VY=VELOCITY      ZY=DRAWDOWN
     REM YR(I)-YRC(I)   VYR(I)-VYRR(I)   ZR(I)-ZRR(I)
     FOR I = 1 TO 5
     dum = B
     YR(I) = (dum + (I - 1) / 4 * (BSIDE - B))
     YRC(I) = YR(I) * RAT + BLRAT + 40
```

Figure 32. (Sheet 8 of 12)

```
                                    yy = ABS(YR(I))
                                    VYR(I) = VRM * EXP(C * (yy - B) / (BSIDE - B))
                                    VYRR(I) = 80 - (VYR(I) * VRAT)
                                    ZR(I) = ZSM * EXP(ZC * (yy - B) / (BSIDE - B))
                                    ZRR(I) = ZR(I) * DRAT + 85
                                    NEXT I

                               REM LOAD LINES INTO LINES.1 FILE
                               OPEN "LINES.1" FOR OUTPUT AS #1
                                 FOR I = 1 TO 5
                                  IF I = 1 THEN
                                   PRINT #1, "BM";
                                   PRINT #1, USING "###"; YLC(I);
                                   PRINT #1, ",";
                                   PRINT #1, USING "###"; VYLR(I);
                                  END IF
                                  IF I > 1 < 5 THEN
                                   PRINT #1, " M";
                                   PRINT #1, USING "###"; YLC(I);
                                   PRINT #1, ",";
                                   PRINT #1, USING "###"; VYLR(I);
                                  END IF
                                  IF I = 5 THEN
                                   PRINT #1, " M";
                                   PRINT #1, USING "###"; YLC(I);
                                   PRINT #1, ",";
                                   PRINT #1, USING "###"; VYLR(I)
                                  END IF
                                 NEXT I
                                 FOR I = 1 TO 5
                                  IF I = 1 THEN
                                   PRINT #1, "BM";
                                   PRINT #1, USING "###"; YLC(I);
                                   PRINT #1, ",";
                                   PRINT #1, USING "###"; ZLR(I);
                                  END IF
                                  IF I > 1 < 5 THEN
                                   PRINT #1, "M";
                                   PRINT #1, USING "###"; YLC(I);
                                   PRINT #1, ",";
                                   PRINT #1, USING "###"; ZLR(I);
                                  END IF
                                  IF I = 5 THEN
                                   PRINT #1, "M";
                                   PRINT #1, USING "###"; YLC(I);
                                   PRINT #1, ",";
                                   PRINT #1, USING "###"; ZLR(I)
                                  END IF
                                 NEXT I
                                 FOR I = 1 TO 5
                                  IF I = 1 THEN
                                   PRINT #1, "BM";
                                   PRINT #1, USING "###"; YRC(I);
                                   PRINT #1, ",";
                                   PRINT #1, USING "###"; VYRR(I);
                                  END IF
                                  IF I > 1 < 5 THEN
                                   PRINT #1, "M";
                                   PRINT #1, USING "###"; YRC(I);
                                   PRINT #1, ",";
```

Figure 32. (Sheet 9 of 12)

```
     PRINT #1, USING "###"; VYRR(I);
     END IF
     IF I = 5 THEN
      PRINT #1, "M";
      PRINT #1, USING "###"; YRC(I);
      PRINT #1, ",";
      PRINT #1, USING "###"; VYRR(I)
     END IF
    NEXT I
    FOR I = 1 TO 5
     IF I = 1 THEN
      PRINT #1, "BM";
      PRINT #1, USING "###"; YRC(I);
      PRINT #1, ",";
      PRINT #1, USING "###"; ZRR(I);
     END IF
     IF 1 < I > 5 THEN
      PRINT #1, "M";
      PRINT #1, USING "###"; YRC(I);
      PRINT #1, ",";
      PRINT #1, USING "###"; ZRR(I);
     END IF
     IF I = 5 THEN
      PRINT #1, "M";
      PRINT #1, USING "###"; YRC(I);
      PRINT #1, ",";
      PRINT #1, USING "###"; ZRR(I)
     END IF
    NEXT I
    CLOSE #1

   REM DRAW LINES THROUGH POINTS
    OPEN "LINES.1" FOR INPUT AS #1
    LINE INPUT #1, LVEL$
    DRAW "X" + VARPTR$(LVEL$)
    LINE INPUT #1, LDRAW$
    DRAW "X" + VARPTR$(LDRAW$)
    LINE INPUT #1, RVEL$
    DRAW "X" + VARPTR$(RVEL$)
    LINE INPUT #1, RDRAW$
    DRAW "X" + VARPTR$(RDRAW$)
    CLOSE #1
    SLEEP
   RETURN

   PAPER:
    CLS
    PRINT
    PRINT "        INSURE YOUR PRINTER IS ON WITH PAPER IN IT"
    FOR I = 1 TO 4
    LPRINT
    NEXT I
    LPRINT TAB(12); "PROGRAM NAVEFF.BAS-SCHIJF METHOD PLUS EMPIRICISM"
    LPRINT
    LPRINT " EXPERIMENTAL DATA USED IN DEVELOPMENT LIMITED TO THE FOLLOWING:"
    LPRINT " BLOCKAGE RATIO LESS THAN 85"
    LPRINT " DISTANCE ON SIDE OF VESSEL GREATER THAN 10% OF TOTAL CHANNEL WIDTH"
    LPRINT "     AND GREATER THAN VESSEL BEAM"
    LPRINT " VESSEL LENGTH GREATER THAN 40% OF CHANNEL WIDTH"
    LPRINT " RETURN VELOCITY AND DRAWDOWN LIMITED TO ONE BEAM WIDTH AWAY"
```

Figure 32. (Sheet 10 of 12)

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```
        LPRINT "      FROM VESSEL CENTERLINE OUT TO THE SHORELINE"
        FOR I = 1 TO 8
        LPRINT
        NEXT I
        LPRINT TAB(25); "DATA SHOWN IS THE INPUT DATA"
        LPRINT
        LPRINT " CHANNEL TOTAL AREA "; USING "######.#"; ATOTAL;
        LPRINT " "; AUNIT$;
        LPRINT "    AREA LEFT OF TOW            "; USING "######.#"; ALEFT;
        LPRINT " "; AUNIT$
        LPRINT "          TOTAL WIDTH "; USING "#####.#"; BTOTAL;
        LPRINT " "; LUNIT$;
        LPRINT "   DISTANCE, LEFT BANK TO TOW "; USING "#####.#"; BLEFT;
        LPRINT " "; LUNIT$
        LPRINT " TOW      WIDTH       "; USING "#####.#"; B;
        LPRINT " "; LUNIT$; "   DRAFT                       "; USING "####.##"; D;
        LPRINT " "; LUNIT$
        LPRINT " TOW      LENGTH       "; USING "#####.#"; L;
        LPRINT " "; LUNIT$
        LPRINT " TOW SPEED RELATIVE TO GROUND       "; USING "####.##"; VG;
        LPRINT " "; VUNIT$
        LPRINT " AVERAGE CHANNEL VELOCITY(+=UPBOUND,-=DOWN) "; USING "####.##"; VAM;
        LPRINT " "; VUNIT$
        LPRINT
        IF VLIMRAT > .35 THEN GOTO 255
        LPRINT "WARNING******** SPEED THRU WATER LESS THAN 0.35*LIMIT SPEED ********
255   IF VLIMRAT < .9 THEN GOTO 257
        LPRINT "WARNING******** SPEED THRU WATER GREATER THAN 0.9*LIMIT SPEED ******
257   REM
      FOR I = 1 TO 5
      LPRINT
      NEXT I
      LPRINT TAB(15); "COMPUTED RETURN VELOCITY AND DRAWDOWN DISTRIBUTION"
      LPRINT
      LPRINT TAB(15); "DISTANCE"; TAB(37); "RETURN"; TAB(54); "DRAWDOWN"
      LPRINT TAB(15); "FROM TOW CL"; TAB(37); "VELOCITY"
      LPRINT TAB(15); LUNIT$; TAB(37); VUNIT$; TAB(54); LUNIT$
      LPRINT
        FOR J = 1 TO 2
        IF J = 2 THEN GOTO 260
        ALF = ALFL: VRM = VRLM
        ZALF = ZALFL: ZSM = ZSML
        BSIDE = BLEFT
        GOTO 270
260   ALF = ALFR: VRM = VRRM
        ZALF = ZALFR: ZSM = ZSMR
        BSIDE = BRIGHT
270   C = 3! * LOG(1 / ALF)
        ZC = 3! * LOG(1 / ZALF)
        '
        '
        YLAST = 0
        FOR I = 1 TO 5
        IF J = 1 THEN dum = -BSIDE
        IF J = 2 THEN dum = B
        Y = (dum + (I - 1) / 4 * (BSIDE - B))
        yy = ABS(Y)
        VY = VRM * EXP(C * (yy - B) / (BSIDE - B))
        ZY = ZSM * EXP(ZC * (yy - B) / (BSIDE - B))
        LOCA$ = " "
```

Figure 32. (Sheet 11 of 12)

```
        IF J = 1 AND I = 1 THEN LOCA$ = "  LEFT BANK"
        IF J = 2 AND I = 5 THEN LOCA$ = "  RIGHT BANK"
        IF (I = 1) AND (J = 1) THEN VYQL = VY: ZLQ = ZY
        IF (I = 1) AND (J = 2) THEN VYQR = VY: ZRQ = ZY
    LPRINT LOCA$;
    LPRINT TAB(15); USING "#####.#"; Y;
    LPRINT TAB(30); USING "########.###"; VY;
    LPRINT TAB(45); USING "##########.###"; ZY
        YLAST = Y
        NEXT I
        NEXT J
    LPRINT CHR$(12)
    RETURN
```

Figure 32. (Sheet 12 of 12)

exceeds the Schijf return velocity and prompts for a new speed. At the end of each tabular output, the program produces a screen image of the cross section, tow, and computed return velocity and drawdown.

Example Problem (based on WC Norman tow on Kampsville trip 1 field data:

a. Determine return velocity and drawdown distribution for a navigation channel having a 359-m top width and 1,309-sq-m cross-sectional area. The tow is 222 m from the left bank which results in a cross-sectional area left of the tow of 800 sq m. The barges draft 2.74 m, have a total beam of 32 m, and a total length of barges of 238 m. The downbound tow travels at 2.9 m/sec relative to ground against an average ambient velocity of 0.49 m/sec.

b. Solution: Enter an "m" to indicate the use of metric units followed by the geometric factors. Enter an average channel velocity of -0.49 m/sec, since this is a downbound tow. Enter a vessel speed relative to ground of 2.9 m/sec. The vessel length is used to ensure the ratio of vessel length/channel width exceeds 0.4 and to compute the displacement thickness to determine the effective draft and beam of the vessel. The program output is shown in Figure 33.

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```
              PROGRAM NAVEFF.BAS-SCHIJF METHOD PLUS EMPIRICISM

EXPERIMENTAL DATA USED IN DEVELOPMENT LIMITED TO THE FOLLOWING:
BLOCKAGE RATIO LESS THAN 85
DISTANCE ON SIDE OF VESSEL GREATER THAN 10% OF TOTAL CHANNEL WIDTH
VESSEL LENGTH GREATER THAN 40% OF CHANNEL WIDTH
RETURN VELOCITY AND DRAWDOWN LIMITED TO ONE BEAM WIDTH AWAY
     FROM VESSEL CENTERLINE OUT TO THE SHORELINE




                        DATA SHOWN IS THE INPUT DATA

CHANNEL TOTAL AREA    1309.0 SQ M    AREA LEFT OF TOW            800.0 SQ M
        TOTAL WIDTH    359.0 METERS  DISTANCE, LEFT BANK TO TOW  222.0 METERS
TOW     WIDTH           32.0 METERS  DRAFT                       2.74 METERS
TOW     LENGTH         238.0 METERS
TOW SPEED RELATIVE TO GROUND          2.90 M/SEC
AVERAGE CHANNEL VELOCITY(+=UPBOUND,-=DOWN)   -0.49 M/SEC




         COMPUTED RETURN VELOCITY AND DRAWDOWN DISTRIBUTION

              DISTANCE              RETURN          DRAWDOWN
              FROM TOW CL           VELOCITY
              METERS                M/SEC           METERS

LEFT BANK     -222.0                0.155           0.049
              -174.5                0.185           0.053
              -127.0                0.220           0.058
               -79.5                0.263           0.064
               -32.0                0.313           0.070
                32.0                0.364           0.084
                58.3                0.324           0.079
                84.5                0.289           0.075
               110.8                0.257           0.071
RIGHT BANK     137.0                0.229           0.067
```

Figure 33. Output from PC program NAVEFF

8 Results and Conclusions

The recommended 1995 analytical method presented herein is based on conservation of energy plus empiricism to define the distribution of return velocity and drawdown. The 1995 analytical method is summarized to compute the following:

 a. Schijf return velocity and drawdown using Equations 1 and 2.

 b. Average return velocity using Equation 13.

 c. Compute average return velocity on each side of the vessel using Equations 14 and 15.

 d. $V_{ra}/V_{rt} = \alpha'$ using Equation 16.

 e. C using Equation 17.

 f. $V_r(Y)$ using Equation 10. $V_r(Y)$ is linearly added to or from ambient currents.

 g. $z(Y)$ using Equations 18 through 22.

The 1995 analytical method should be limited to:

 a. N less than 85. While the vast majority of the data had N < 52, the limited data from the Clark's Ferry pool 572.7 physical model tests for N of about 85 resulted in significant scatter but exhibited the correct trend about the line of perfect agreement.

 b. Tow length greater than 40 percent of the channel width.

 c. Distance on both sides of tow center line equal to or greater than 10 percent of the total channel width.

 d. Distance Y from the tow center line greater than tow width B.

 e. Vessel speed equal to 35 to 90 percent of the limiting speed.

f. The predictive method presented herein, is applicable to river reaches that can be characterized by a single cross section. One would not expect these techniques to provide valid results at the end of an island or in other areas where the cross section varies rapidly.

Areas of needed research for this method are more data for N greater than 52, variable tow length less than 0.4 times the channel width, and better data supporting the distribution of water-level drawdown. Future versions of the NAVEFF model will include propeller jet effects as well as short-period wave activity.

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Appendix A
Notation

A_c Undisturbed channel area

A_w Disturbed channel area around midsection of vessel

A_m Submerged cross-sectional area of vessel at midsection

β Coefficient that varies with V/V_L in the Schijf equations to improve agreement between observed and computed return velocity and drawdown.

B_o Channel width

B Beam of vessel

B_{side} Distance from vessel center line to shoreline

g Gravitational acceleration

h Undisturbed average water depth

L Vessel length

N Ratio of channel cross-sectional area to vessel cross-sectional area

V the vessel speed

V_L Maximum speed (called the critical or limiting speed)

V_r Average return velocity

V_{rm} Maximum return velocity

V_{rs} Average return velocity for each side of vessel

V_{rsm} Maximum return velocity on each side of the tow

$V_r(Y)$ Maximum return velocity during tow event

Y Distance from center line of vessel

z Average water-level drawdown

Z_{rs} Average drawdown for each side of vessel

Z_{sm} Maximum drawdown for each side of vessel

$Z(Y)$ Maximum water-level drawdown during tow event

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13. ABSTRACT (Maximum 200 words)

An analytical method for estimating return velocity and drawdown is developed based on physical model study data for the Kampsville reach, Illinois River and the Clark's Ferry reach, Mississippi River. The analytical method uses conservation of energy plus empiricism to define the distribution of maximum return velocity and maximum drawdown during the tow event. The method is compared to prototype return velocity and drawdown data from two sites on the Illinois River, two on the Mississippi River, and four on the Ohio River.

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